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PhD Thesis

Energy Savings Vs. Energy Supply Modelling Energy Systems

Mattia Baldini

January, 2019

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Preface

This thesis was carried out at the Energy System Analysis Division, DTU Management Engineering (Technical University of Denmark) in partial fulfilment of the thesis requirements for the degree of Doctor of Philosophy (Ph.D.).

The PhD research has been funded by the Danish Innovation Fund as part of the interdisciplinary research project SAVE-E and was conducted from October 2015 to January 2019, under the supervision of Professor Henrik Klinge Jacobsen. Part of the research, five month in spring 2018, has been conducted at the Simon Fraser University in Vancouver, Canada, under the supervision of Professor Mark Jaccard.

The thesis consists of two parts. The first part introduces the thesis background and motivation, providing an overview of methods applied, considerations about the results achieved and future works. The second part consists of five research chapters, based on academic papers that are either published or submitted in international peer-reviewed journals. The five main papers proposed are co-authored, and they are each self contained in terms notation and data employed, and with separate bibliographies.

Kgs. Lyngby, Denmark, January 2019

Mattia Baldini

Summary

Energy efficiency is part of the plans for a decarbonised and fossil-fuels independent future, and it is expected to cover an essential role to reduce green-house gasses emissions. Albeit consistent sectorial energy savings options are available, a thorough overview of which sectors possess the most cost-effective options do not exist, particularly from an energy systems viewpoint. This thesis investigates on cost-effective energy saving measures, evaluating investments in the framework of interconnected energy systems, from a socioeconomic and private end-user perspective. The main objective is explored thoroughly by means of developing modelling studies in diverse demand areas, seeking optimal levels of heat and electricity savings opportunities in the household and industry sector, combining engineering-economic methods.

This dissertation is developed by considering different approaches and methods: (i) Investigation on methods to identify optimal trade-offs between energy efficiency improvements and additional renewable energy supply; (ii) Assessment of optimal households electricity saving investments, from a consumer and energy systems perspective; (iii) Analysis on the influence of socioeconomic and behavioural factors for investments in energy efficient household appliances; (iv) Evaluation of cost-effective heat conservation measures in residential sector, focusing on changes in district heat-tariffs to foster consumer investments; and (v) Modelling of industrial characteristics in the framework of an energy systems model, to investigate industrial processes and options for energy savings and fuel-switching.

Each task addresses attractive energy saving measures with multidisciplinary methodologies tailored to the scope of the analysis, leveraging tools ranging from energy systems analysis, consumer investment models and economical assessment based on net present value of investments. Existing methodologies are thus tested and extended according to the needs. Balmorel, a bottom-up energy systems model with high levels of details in regard to energy supply and technologies, is used to perform energy systems analyses. To identify optimal levels of cost-effective saving measures under different objectives, the model is extended in several ways: first including specifics about absolute and temporal characteristics of end-use sectors energy demand; second, including investment opportunities in heat and electricity energy saving measures.

The thesis contributes with modelling techniques, methodologies, applications and policies, illustrating what makes end-use sectors invest in energy savings. Based on the knowledge of cost-effective savings and resulting effects at energy systems and consumer level, the findings pave the way for designing new and more efficient policy instruments, highlighting a more cost-effective way to reach energy savings, renewables and climate targets for Denmark.

Resumé (Danish Summary)

Energieffektivisering er en del af planerne for en fremtid uafhængig af kuldioxid og fossile brændstoffer. Det forventes at energieffektivisering vil spille en væsentlig rolle i reduceringen af udledning af drivhusgasser. Selv om diverse konsekvente sektorspecifikke energibesparelsesmuligheder er tilgængelige, er der ikke overblik over hvilke potentialer, der er de mest omkostningseffektive, specielt i et energi system perspektiv. Ud fra både et socioøkonomisk- og privat -perspektiv undersøger denne afhandling omkostningseffektive energibesparende foranstaltninger og evaluerer investeringer inden for rammen af sammenkoblede energisystemer. Problemstillingen i denne afhandling belyses ligeledes gennem case-studier, der identificerer optimale varme- og el besparelser i husstands- og industrisektoren, dette gennem en kombination af tekniske og økonomiske udgangspunkterog metoder.

Denne afhandling er udarbejdet under overvejelse af forskellige tilgange og metoder: i) Undersøgelse af metoder til at identificere optimal afvejning mellem energieffektivisering og forsyning af vedvarende energi; ii) Vurdering af elbesparende investeringer i husholdninger fra henholdsvis et forbruger- og energisystemperspektiv; iii) Analyse af den indflydelse socioøkonomiske- og adfærdsmæssige faktorer har på investeringer i energiforbrugende apparater; iv) Evaluering af omkostningseffektive varmebesparelser i boliger, med fokus på effekt af ændringer i fjernvarmetariffer; og (v) Modellering af karakteristika for industriens energi-efterspørgsel inden for rammen af en energisystemmodel for at undersøge betydningen af industrielle processer for mulige energibesparelser og brændselssubstitution.

Hvert element i analysen adresserer attraktive energibesparende foranstaltninger gennem tværfaglige metoder, der er skræddersyet til analysens anvendelsesområde, værktøjer, der spænder fra energisystemanalyser, investeringsmodeller og økonomisk vurdering baseret på investeringers nutidsværdi. Eksisterende metoder testes og udvides således efter behov. Balmorel, en bottom-up energisystemmodel med mange detaljer med hensyn til energiforsyning og -teknologi, udvides til en meget detaljeret beskrivelse af energi efterspørgsel, der

muliggør integrerede analyser af omkostningseffektive energibesparelser. For at identificere optimale niveauer af omkostningseffektive besparelsesforanstaltninger under forskellige målsætninger udvides modellen på flere punkter: først med specifikationer om absolutte og tidsmæssige fordelingaf slutbrugerens energibehov; for det andet, investeringsmuligheder i varme- og elbesparende foranstaltninger.

Afhandlingen bidrager med modelleringsteknikker, metoder, applikationer og analyse af politikker, der illustrerer, hvad der har betydning for slutbrugerens investeringer i energibesparelser. Baseret på kendskabet til omkostningseffektive besparelser og effekter på energisystemer og forbrugerniveau, vil resultaterne lede til design af nye og mere effektive politik-instrumenter, der kan identificere en mere omkostningseffektiv måde at nå både energibesparelser, vedvarende energi- og klimamål for Danmark.

Acknowledgements

This thesis is the product of a long journey, started three years ago at the end of the master. If I look back when I started, I could see a young and naive student, eager to learn everything about energy and contribute to solve the world's energy problems. The PhD experience has surely been useful to get things into perspective, and helped me to become a better and more critical researcher.

For this, I would like to thank all the people that have been part of the journey.

Firstly, I want to thank Henrik, my supervisor, who agreed to be part of the journey from the first day. Henrik has supported and guided me during the last three years, both at academic and personal level, providing constructive feedbacks and suggestions for improvements. The time spent discussing research, cultural views and opinions has been surely valuable and enjoyable.

Secondly, I want to thank all of my colleagues from Systems Analysis for creating such a nice working environment every single day of the last three years. The table-football breaks, the social activities, and the enjoyable talks at lunch breaks have been just the right amount of distractions that I needed to get through, even during the toughest days. It has been a pleasure to share with you every single day of this journey.

Many thanks also to Mark Jaccard, Bradford Griffin, Aaron Pardy, Shahid Hossaini, Thomas Budd and all the colleagues in the Energy and Materials Research Group (EMRG) and in the Canadian Industrial Energy End-use Data and Analysis Centre (CIEEDAC) labs at the Simon Fraser University in Vancouver, Canada. The daily discussions, challenges and insight on the Canadian approach to the energy field has surely enhanced the quality of my research and my ability to be critic about today's energy challenges. Not to forget about all the friends and flatmates that made every moment more enjoyable, Clementina, Jessica, Luca, Spencer, Tian, Oscar and Kate. The oversea adventure has been an unforgettable and valuable experience, thanks to all of you for being part of it.

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Finally, a special thanks to my family who has consistently supported me and surrounded me with joy: mamma, papá, Cami e Luca, grazie di tutto!

These three years have been extremely intense and challenging, but luckily I was surrounded by amazing people who made this journey possible.

List of publications

Articles included in the thesis

Baldini, M. and H. Klinge Jacobsen (2016). "Optimal trade-offs between Energy Efficiency improvements and additional Renewable Energy supply: A review of international experiences". In: *Conference proceeding for European Electricity Market EEM16*. URL: http://ieeexplore.ieee.org/document/7521245/

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Wiese, F. and M. Baldini (2018). "Conceptual model of the industry sector in an energy system model: A case study for Denmark". In: *Journal of Cleaner Production* 203. DOI: 10.1016/j.jclepro.2018.08.229.

Articles not included in the thesis

Nielsen, L. H., M. Baldini, K. Skytte, C. H. Pérez, E. C. García, D. L. Barrio, L. G.Cuadrado, and A. R. Rocha (2016). "Feasibility Study on HYSOL CSP". In: *Int. J. of Thermal & Environmental Engineering* 13. DOI: 10.5383/ijtee.13.01.008.

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Contents

Part I

Introduction

"There are two types of resources.
The finite resources, like fossil energy, money and sand;
their effect is immediate, but the more we share, the less we have.
Then there are the infinite resources, like renewables, knowledge, love and efficiency;
the more we share, the more they grow, but sharing needs time."

Benoit LEBOT, Executive director, IPEEC

Chapter 1

Introduction

The Paris international agreement, tackling the upcoming challenges about climate change and emissions, has highlighted the need of a drastic reduction of the human-energy related greenhouse gasses (GHG) emissions (UNFCCC, 2018). Analogous considerations are presented in the latest Intergovernmental Panel Climate Change international report, investigating on the global consequences of the 1.5° C increase of the world's temperature (IPCC, 2018). The fundamental conclusions suggest, among other, a prompt transformation of the way to generate and utilise energy, to limit the emissions of carbon dioxide (CO_2). In this framework of transformation, energy efficiency (EE) and renewable energy sources (RES) are expected to be the key actors of a future where the use of fossil will be limited (if not extinguished) and the levels of GHG emissions will be lowered consistently.

When evaluated in the framework of energy systems, examples from the literature show that policies focusing uniquely on RES targets or on specific energy saving measures can lead to socioeconomic sub-optimal solutions, as energy savings influence energy supply and investments in supply technologies can potentially lock-out socioeconomic feasible energy savings (Taseska-Gjorgievska et al., 2013; López-Peña et al., 2012; Mallah and Bansal, 2010). To find a balanced trade-off between a demand side with potential savings and the supply side with RES options, investments in energy savings and in supply technologies should thus be optimised simultaneously, using energy systems models.

In relation to energy efficiency, the literature highlights that there is an un-exploited potential, varying in size and shape according to the area considered. For instance, from a bottom-up perspective, in the household sector, energy efficiency can be achieved by adopting more efficient household appliances, using e.g. the energy consumption labelling system A-G proposed by the European Union (EU) to furnish the house with less energy consuming devices (European Commission, 1992). Otherwise, energy efficiency can be gained by improving the building performances, in order to reduce the use of heat energy; hence, walls insulation, double glazed windows or better insulated ceilings and floors can be considered as energy conservation measures contributing to the reduction of the energy needs (Brøgger and Wittchen, 2018; Wittchen and Kragh, 2013).

Likewise, in the industrial sector the uncovered potential for energy efficiency can be located in the performance of the processes, or in the re-utilisation of the outputs, to decrease the net energy inputs; for instance, re-utilising the excess heat from industrial processes to pre-heat the air, increasing the inlet temperature in the processing, hence requiring a lower input of energy to achieve the same output (Danish Energy Agency, 2015). Furthermore, energy efficiency can extend beyond the physical concept and consider not only the quantitative component (intended as the possibility to make an end-use or a device consume less, while delivering the same service) but also the qualitative component (intended as the use of a device). According to the literature, energy efficiency refers to the technical ratio between the quantity of primary or final energy consumed and the maximum quantity of energy service obtainable (heating, lighting, cooling). On the other hand, energy savings implies the reduction of final energy consumption, through energy efficiency improvements or behavioural change, intended as the change of a consumer behaviour, which turns into a smarter (and lower) use of energy, while enjoying the same service (Baldini and Klinge Jacobsen, 2016). In this thesis, both concepts represent the target of the analyses, aiming at reducing energy consumption and GHG emissions.

Although the potentials for energy savings are consistent, there is often a discrepancy between the range of technical options available and the measures actually implemented, driving researchers to investigate on which options can truly be relevant to consider, according to different perspectives. The literature acknowledges the existence of such a gap, and refers to that as the "Energy Efficiency Gap (EEG)". The barriers that hinder the adoption and implementation of energy savings can be multiple and can vary according to the case. Among other, there can be inappropriate methods in assessing attractive investments, misjudgements regarding the appropriate measure, misinformation at the moment of choice, omission of intangible (transaction) costs as well as policy, economic and technical limits. Each of these barriers can slow the potential adoption of energy savings interventions, leading to sub-optimal configurations which, consequently, lowers the contribution of EE to the GHG emission reduction. Henceforth it is first paramount to investigate on the primary movers and impacts behind investments in energy savings interventions; then, develop mechanisms and methods to overcome the barriers and facilitate the uptake of energy savings.

In relation to the different topics involved for such analyses, the methodologies adopted should consider the wider multidisciplinary competences required for the case studies. For instance, when studying energy systems impact of adopting energy efficient household appliances, the study fields involved in the analysis should extend not only to energy systems analysis and modelling of energy savings, but also to the field of consumer behaviour, to understand which characteristics would actually drive an end-user to adopt energy efficient measures. Likewise, as electricity and heat conservation measures compete with different commodities subject to different market rules (i.e. electricity and heat), it is fundamental to contextualise the analysis, before assessing potentials and attractive energy savings interventions. Similar considerations extend also to different sectors considered, as e.g. household and industry are subject to different tariff conditions and are characterised by different consumption loads and end-uses.

As the considerations related to energy savings are (and can become) wide and extensive, the thesis narrows the scope of the analyses, limiting the investigations to few among the main topics, yet considering the fundamental aspects of the multidisciplinary approaches involved with energy savings. Hence, this thesis addresses and explores both broader and more specific research questions.

From a broader perspective, the thesis focuses on:

1. understanding the additional value of modelling energy savings investments in bottom-up energy systems models;
2. investigating the additional benefits of modelling in details temporal profiles of energy savings and consumption, for the end-use sectors;
3. exploring what are the modelling effects of using different types of methodologies while investigating on attractive energy savings investments;

Specifically, the thesis provides indications in regard to the following research questions:

- What are the characteristics of the most common models and methodologies to investigate on the optimal trade-offs between energy efficiency improvements and additional renewable energy supply, under different objectives?
- How can we assess optimal investments in households electricity saving, from a consumer and energy systems perspective, and which impact do they have on the energy systems? Which socioeconomic and behavioural factors can influence the choice of investments in energy efficient household appliances?
- How to assess the cost-effectiveness of building-tailored heat energy conservation measures, for a residential building stock in a district heating area, from an end-user perspective, under different conditions? Is there an effect on exposing the

private consumer to different heat tariffs, in relation to a potential uptake of energy savings measures?

- Which aspects characterise the structure of the industry and how can we adequately model a sector characterised by various end-uses and integrate it in established bottom-up energy systems models? Which benefits does the modelling gain by considering detailed temporal profiles of energy consumption?

To address the research questions, the thesis considered distinct methodologies tailored to the case study under analysis, ranging from energy systems modelling to consumer investment models. The thesis contributes to the field by extending existing models and developing novel methodologies, resulting in practical findings that can be useful for researchers, policy makers and governmental institutions. By providing directions for attractive potentials and incentives to promote the cost-efficient saving investment from different perspectives, based on empirical results from case studies applied in different end-use sectors, the thesis provides insights on the system value of different types of energy savings, paving the way for actions that will contribute to a decarbonised future.

1.1 The SAVE-E project

In this framework, the interdisciplinary research SAVE-E project ("SAVE-E Energy Savings: Closing the Energy Efficiency Gap"), funded by the Danish Innovation Fund, aims at identifying relevant behavioural, technical and policy factors influencing the energy efficiency gap (Technical University of Denmark, 2015). The goal of the research is to examine what makes Danish households and companies invest in energy saving solutions, combining potentials, barriers and strategies for implementing targeted improvements.

The SAVE-E project considers seven work packages (WPs). Each WP investigates on the specific aspects of the problem by developing qualitative and quantitative models, methods, and performing engineering-economic analyses. The work developed during this PhD thesis is part of the WP5, researching on the optimal trade-off between savings and supply, when meeting GHG reduction targets under different policy scenarios for Denmark. The trade-off is analysed by extending the bottom-up energy systems model Balmorel to include energy saving investments in various end-use sectors. In accordance with large energy data availability and modelling experiences, the studies focus on Danish cases. On the bases of engineering-economic approaches, WP5 derives recommendations on how to surmount the EEG from a socioeconomic and private perspective, while balancing the trade-off between efficiency improvements and supply from renewable energy sources.

1.2 Thesis Outline

The dissertation consists of two parts:

Part I: Introduction
After the introduction, the thesis elaborates on the multidisciplinary approaches involved in the field of energy savings, in Chapter 2, and on the methods adopted to identify attractive energy savings interventions, in Chapter 3. Chapter 4 reports an overview of the methodological and empirical contributions from the case studies. Chapter 5 concludes the dissertation highlighting the relevance of the findings and proposing future works.

Part II: Research work
The second part of the dissertation provides an overview of the academic journal papers, relevant to the scope of the SAVE-E project. Part II considers five manuscripts:

- **Paper 1** is a conference proceeding from the *European Electricity Markets EEM16*. It is a literature review of existing models and methods to investigate on the trade-offs between energy efficiency improvements and additional renewable energy supply. (Baldini and Klinge Jacobsen, 2016).
- **Paper 2** is a journal paper published in *Energy Efficiency*. The paper proposes a method to model the electricity savings in the households sector considering temporal profiles of consumption of household appliances. The model provides indications on the most attractive energy savings investments from an energy system and end-user perspective, using the Balmorel model. (Baldini and Trivella, 2017).
- **Paper 3** is a journal paper published in *Energy Policy*. The paper proposes a method to assess how (and which) end-user socioeconomic and behavioural factors can influence the purchase of energy efficient household appliances. The study suggests improved information campaigns by targeting key demographics, to drive high efficiency investments. (Baldini et al., 2018).
- **Paper 4** is a journal paper prepared for submission in *Applied Energy*. The paper investigates on cost-effective energy savings measures, for a sample building stock in the city of Aarhus. The study develops a method to assess attractive options based on different structures of the district heating tariffs, suggesting policies to foster the uptake of energy savings interventions. (Baldini et al., 2019)
- **Paper 5** is a journal paper published in the *Journal of Cleaner Production*. The paper proposes a method to optimise operational aspects of the industry sector, in the framework on the energy system model Balmorel, considering temporal profiles of energy consumption. The study creates a benchmark for analyses that can focus simultaneously on the impact of changes in the industry and in the energy sector, on a system wide scale. (Wiese and Baldini, 2018).

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Chapter 2

Energy savings: approaches and challenges

Among the mitigation measures for a low carbon development of future energy systems, energy efficiency and energy savings are identified as the primary keystones of the transformation, for the adoption of energy savings can lead to numerous benefits, primarily economical and environmental.

Economical benefits are linked with the reduced consumption, as a lower energy demand can induce savings on the energy bill (e.g., for end-consumer) or on the cost of energy production based on the supply technologies available (e.g., for energy systems). Furthermore, for some cases, the initial investment costs can be paid-off considering the energy savings throughout the lifetime of the measure; the economical gains achieved after the break-even can be considered as net economical savings. In other words, the additional costs of efficient appliances can be potentially offset by the saved energy costs over the lifetime of technologies (Wada et al., 2012).

Environmental benefits are linked with lower need of energy production, as energy generation includes externalities, such as CO_2 emissions. The extent of the environmental savings can vary, e.g. in relation to the portfolio of technologies composing the energy system under study. Intuitively the same unit of energy saved (e.g., MWh) can bring more benefits for systems highly based on fossil fuel based technologies, compared to others with a higher share of renewable energy sources (Baldini and Trivella, 2017). A similar discussion can be extended for other end-use cases, considering the inputs that energy savings would replace (e.g., fossil fuels for industrial processes).

In spite of the complementary benefits, energy saving potentials still remain untapped for sectors such as industry, transport, and buildings (IEA, 2018). The literature have thus been focusing on elements slowing the development and adoption of energy savings to optimal levels. Four key questions are the focus of debate: (1) Where are located the energy savings; (2) What are the approaches and fields of study involved in the investigation on attractive potentials; (3) Which models and methodologies can provide indications on attractive investments and the related energy systems effects; and (4) What is the contribution of policies to foster the uptake of energy savings interventions.

Each of the journal papers in Part II includes a literature review tailored to the case study, in regard to the listed arguments. Hence, the following sections mean to provide an overview of the fundamental aspects involved with energy saving from a broader perspective, in line with the four key questions reported.

2.1 Identifying energy savings

Opportunities for energy savings potentials are available in different forms, for end-use sectors of an economy. According to the recent IEA Energy Efficiency Outlook, based on the Efficient World Scenario for 2040, energy efficiency and energy savings could contribute to reduce energy usage up to 22%, 15% and 15% for transport, industry and buildings (IEA, 2018). Interventions aiming at reducing energy consumption consider improvements in, among other, steam boilers, process heat and motors, for industry; cars, trucks and ships, for transport; heating/cooling and appliances for the building sector.

From a technical (or quantitative) perspective, the potentials for energy savings can be determined comparing the current technology in use with the cutting edge technology in the field, delivering the same service with lower energy input. Energy labelling systems have been put in place to facilitate the comparison and the assessment, particularly in the household sector. For instance, in Europe household appliances and buildings are categorised according to the characteristics of consumption, respectively on the bases of the A^{+++} - G (EU, 2010a) and the A - G Energy Performance Certificates (EPC) scales (EU, 2010b). A similar approach is implemented in the industrial sector, to evaluate the performances of industrial products, such as electric motors and fans (EU, 2018).

Energy savings can also be achieved, from a behavioural perspective, through changes in lifestyles and practices in regard to energy use. The literature reports examples about how lifestyle and behaviour changes can impact energy consumption and consistently reduce it, particularly in the household sector (Zhou and Teng, 2013; Gram-Hanssen, 2014; Frederiks et al., 2015). Savings through behavioural changes can also be attractive in the industry sector, as they can deliver benefits without requiring capital investments. This is particularly relevant in relation to the short pay back time usually required for investments in industrial energy savings, due to the short horizon considered for the return of capital. In spite of the attractiveness, there hasn't been a great focus on non-technical solutions, as it seems to be easier to buy a new motor than teach personnel to run the existing motor differently (Van-Renssen, 2016).

During the thesis work, when identifying the energy savings, we did not develop our own saving potentials, but we relied on previous research and/or market observations. Only in **Paper 4**, among all the journal papers in Part II, we compute our own potentials, based on ground work developed by Brøgger and Wittchen (2018). In regard to the other analyses performed, the extensive use of data is documented on each paper.

2.2 Managing savings potentials: fields of study

When managing savings potentials, there are various approaches and fields of study involved, according to the areas under study; Figure 2.1 provides a graphical overview. From a bottom-up perspective, the identification of cost-effective savings should require a broad knowledge about the technical specifics, the users, the sector and the energy systems considered. Furthermore, policies can be available and applied to different levels to facilitate interventions and investments. In Figure 2.1 we report a list of different potential approaches (levels), with the related field of study (e.g., energy systems, consumer behaviour, policies development,...), which we believe to be important when evaluating energy savings investments, in relation to vast untapped potential.

Level 1 - Technical specifics: Starting from the bottom, the first step includes the technologies. These are the bases of the energy savings, as they are the energy consuming devices. The analysis of saving potentials at this level varies according to the technology considered and it can be more or less challenging, in relation to functioning of the process and the inputs/outputs involved. For instance, while household appliances provide a service consuming only electricity, various inputs and outputs can be involved with industrial end-uses for process heat.

Level 2 - Consumer behaviour: The second step include the end-users, i.e. the heterogeneous actors managing the technologies. This involves the field of practices, consumer behaviour changes and choices investigating, among other, on the reasons behind the use of energy or the adoption of energy savings interventions (i.e. "which socioeconomic characteristics define a consumer's choice?" or "How does a consumer choose a particular saving measure, in relation to her/his attitude toward energy use?").

Level 3 - Sectoral considerations: The third step considers specifics typical of the sector, which can characterise choices in the other levels. Specifics tailored to the sector can include different tariffs (e.g., for electricity or input fuels), goals (i.e. household service vs industrial final products) or structure, thus requiring a separate analysis.

Level 4 - Energy systems modelling: The fourth step includes the energy systems perspective, which can be considered as the comprehensive level. Analysis on the systems impact of savings requires energy systems modelling, including characteristics about optimisation of energy generation and transmission.

Level 5 - Energy savings policies: Finally, the last step considers the policies involved, which can be seen as the drivers for investments and changes in all the levels beneath. They are related with the field of policies design and implementation, and have an impact on the overall structure.

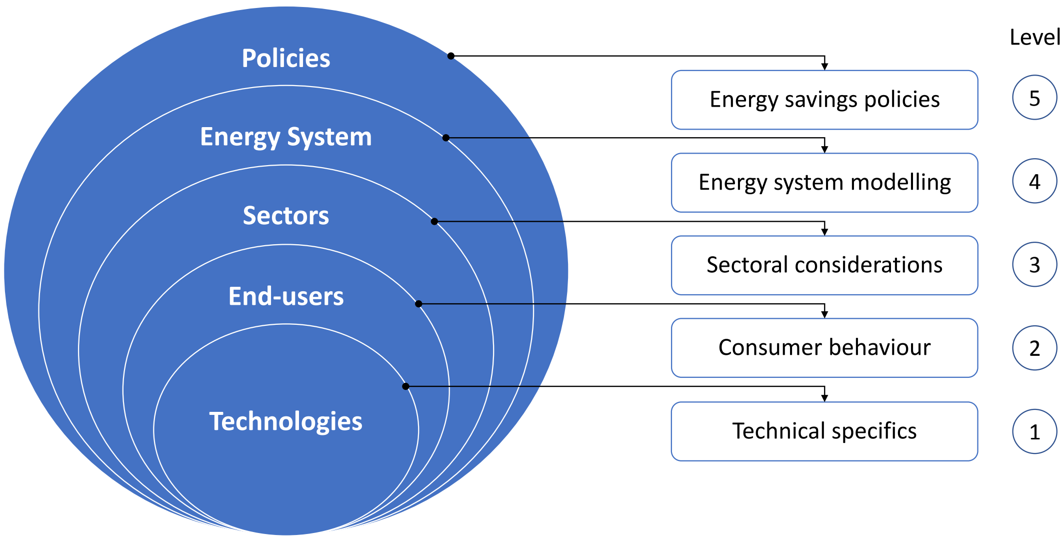

Figure 2.1: Fields of study involved with energy savings.

The different competences involved can be complementary and can enhance the quality of the outcomes related to the uptake of energy savings. The thesis involves, with a different extent, the fields of study reported, varying the focus according to the scope of the research questions of the journal paper.

For instance, **Paper 1** focuses mostly on level 4, explaining models and methodologies involved to assess investments in savings and renewable energy technologies from systems perspective. **Paper 2** considers levels 1 to 4, focusing on efficient household appliances from a private end-user and systems perspective, touching upon consumer behavioural components. **Paper 3** is fully focused on level 2, 3 and 5 investigating on socioeconomic and behavioural characteristics that can influence the purchase propensity of household efficient appliances, from a residential end-user perspective. **Paper 4** considers levels 1-3 and 5 investigating on the cost-effective investments in energy conservation measures from a private residential perspective, including details about policies and changes to heat-tariff structure. Last, **Paper 5** considers levels 1, 3, 4 and 5 in regard to integration and modelling of specifics about the industry sector within an energy systems model.

2.3 Untapping the tapped potentials: approaches and methodologies

The characteristics about the levels illustrated in Figure 2.1 should be part of methodologies investigating on attractive saving investments from different perspectives and the related energy systems effects. The literature presents different examples of models focusing, with different extents, on the details of the levels reported. The two methodologies which are mostly relevant in regard to the work performed during the thesis are: energy systems and consumer choice models.

2.3.1 Energy systems models

Energy systems models are often adopted to perform analyses investigating on various aspects of energy systems, such as scheduling and dispatch of power plants and power transmission, optimal investments in energy technologies under different policy scenarios, or energy systems impacts of new measures (e.g., renewables, savings, electric cars, etc.). The literature highlights three main categories of energy systems models: bottom-up, hybrid and top-down (Ringkjøb et al., 2018). Figure 2.2 reports a graphical overview, placing the models according to basic features.

Bottom-up models are mostly adopted to estimate particulars about technologies and engineering specifics. As Figure 2.2 illustrates, bottom-up models perform well in terms of technological explicitness. Consequently, this approach is usually preferred by users who are interested in detailed technological changes, and how these influence, e.g. energy systems operations and overall GHG emissions. On the other hand, bottom-up models often lack of behavioural realism and consider a partial equilibrium, thus neglecting many of the economic-wide costs. Furthermore, these models usually miss to represent the full social costs of technological change inducted, neglecting other important factors, such as acceptance of the consumers or behavioural realism, that could pose a relevant impact (Jaccard and Dennis, 2006).

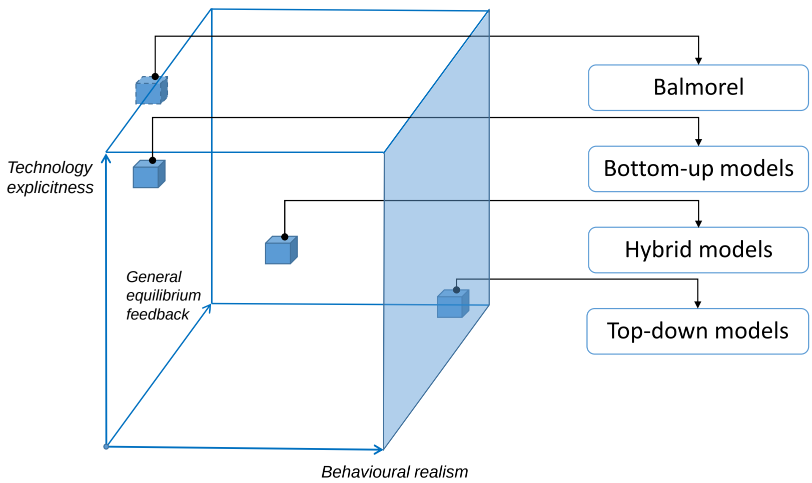

Figure 2.2: Characteristics of energy systems models (Adapted from Andersen S. and Termansen, 2013; Jaccard, 2009).

Top-down models focus on the use of aggregated market data to study the wide-socioeconomic impact of sectoral changes. Policy makers usually use these models as their application provides solutions, on an economy-wide scale, of changes in individual sectors, based on an extensive equilibrium framework (reason for which these models are also known as computed general equilibrium). Nonetheless, top-down models often lack of clarity in terms of technology explicitness, making them in-perfect to assess how the implemented policies change the characteristics and financial costs of the singular technologies ("Skip" Laitner and Hanson, 2006).

Hybrid model can be placed in between, as they combine the technology explicitness of the bottom-up with the behavioural realism of the top-down models (Jaccard and Dennis, 2006). The linking is implemented as mean of compensation for the limitations of one approach or the other. The use of these tools for analyses can provide a better insight on the impact of changes within the whole analysed systems both from an economic-wide and technology-explicitness perspective (Andersen S. and Termansen, 2013).

The decision of the tool for an analysis can be driven by the extent of the study, the depth of investigation and by the dimensional assessment of the analysis. Regarding studies about energy systems impact of savings, the literature present various cases. For instance, Murphy and Jaccard (2011) compares results from bottom-up and hybrid models, using the hybrid model CIMS, while investigating on energy efficiency and the cost of GHG abatement. Alternatively, Zvingilaite (2013); Zvingilaite and Balyk (2014); Zvingilaite and Klinge Jacobsen (2015) use Balmorel, a bottom-up energy systems optimisation model to assess attractiveness and impact of residential heat savings in the building sector. Similarly, assessing trade-offs between district heating and heat supply with heat savings to decarbonise the EU energy system, Connolly et al. (2014); Hansen et al. (2016) use the bottom-up energy model energyPLAN. López-Peña et al. (2012) also use a bottom-up and partial equilibrium model of the energy sector, MASTER.SO, to analyse the impact of support for renewables Vs efficiency. On the other hand, using the computable general equilibrium (CGE) model AMIGA, "Skip" Laitner and Hanson (2006) analyse changes in efficiency and technology investments in the commercial health care sector.

Among the many tools available in the literature, the model adopted for the thesis work is Balmorel, a bottom-up energy systems model. The choice is motivated mainly by the following reasons:

1. the Balmorel model was recommended as a tool for the project SAVE-E, considering the expertise available from the development group within the DTU Management department;

2. Balmorel include high-level of details about the composition of the Danish Energy system, in terms of generation technologies, transmission, temporal profiles of energy consumption at hourly scale and interconnections with neighbouring countries, making that a suitable tool for the Danish cases under study;

3. Balmorel includes a flexible framework of specifics about technologies, sectoral characteristics, energy systems modelling and policies, easing an analysis of the simultaneous impact of energy savings in the framework of energy systems, including the multiple study fields presented in Figure 2.1;

4. the expansion of the model, to consider energy savings investments in different end-use sector, can potentially enhance the quality of the simulations performed. As the model is currently used and applied not only in Denmark, but also in other locations in the world, both in private, governmental and educational institutions, the development will contribute to the quality of the results for future international research.

Further specifics about the theoretical framework of the Balmorel model are reported in Section 3.1.

2.3.2 Consumer choice methodologies

Figure 2.2 locates Balmorel according to model characteristics available at the beginning of the PhD; at this stage, the model was classified as a partial equilibrium, energy systems model[1]. Although it considered the possibility to include price elastic demand (which might resemble broad behavioural aspects), this was considered at an aggregated level, without distinguishing among demand consumer groups and without including aspects about consumer choices with behavioural components.

As part of the analyses performed, in line with Figure 2.1, involve practices, consumer behaviour and choices, the model could benefit from the addition of new functionalities, to consider investigations on the reasons behind e.g. the use of energy or socioeconomic characteristics influencing the adoption of energy savings interventions, from a private consumer perspective. Furthermore, additional methodologies, separate from the model Balmorel, could provide further insights and in-depth analyses, in regard to description of consumer choices with behavioural components.

To this end, the literature presents different cases of methodologies adopted. For instance, Ameli and Brandt (2015) use a discrete choice model, based on logit regression, to estimate determinants of households' investment in energy efficiency and renewables; similarly, Mills and Schleich (2010) adopt a statistical regression model to estimate the relationship between household attributes and choice of a class-A appliance. Alternatively, Gaspar and Antunes (2011) use binomial logistic regression to estimate choice determinants for energy efficiency and appliance purchases in Europe, while Qiu et al. (2014) use both probit models and count data models, to assess the relationship between homeowner risk preferences and energy efficient home improvements (probit) and how risk preferences affect the intensity of energy efficiency improvements by analysing the number of measures adopted by homeowners (count data).

Inspired from the literature, part of the studies presented in the thesis are based on two main approaches: in Baldini and Trivella (2017), we use a simple linear probability model as purpose-build consumer investment model. Although simple, it represents a first step to integrate behavioural aspects in Balmorel. Subsequently, on the bases of a survey performed by the Danish Energy Agency, in Baldini et al. (2018) we develop a more realistic consumer investment model (i.e. logistic regression model), accounting for socioeconomic, demographic and behavioural variables, while trying to capture non-

[1]The core-version of Balmorel is under continuous evolution in relation to uses and modifications for diverse projects and institutions. Such work often translates in additional functionalities for the model which can be extended to all researchers. The work performed in this thesis is based on the DTU Balmorel version from 2016.

rational influences on consumer choices for energy savings options. Further details about the methods are reported in Section 3.3.

2.4 Role of policies fostering energy savings

Policy instruments targeting energy savings have the key role of supporting and fostering the development of interventions, acting on the barriers that hinder the adoption. To this end, energy efficiency policies promote energy efficiency and savings at the different end-use levels, for instance supporting investments in energy efficient technologies and products or providing incentives to inform how to save energy through behavioural changes.

The range of policies related with energy savings is broad, most often tailored to the case and conditions under study. Hence, the aim of the section is to present common forms of support for energy savings, as they will be employed for discussion in the journal papers. To this end, according to (Wiese et al., 2018), existing policies instruments can be grouped in five main categories: market based instruments, financial incentives, regulatory and non-regulatory measures and information-and-feedback.

Market based instruments are policies that enforce additional costs to the energy price, to compensate for the low price of energy, as it usually does not include external costs caused by energy production and consumption (e.g., pollution or health issues related with emissions) (Stiglitz and Rosengard, 2015). For instance, imposing a tax on energy consumption or on emissions can be an approach to induce direct and indirect incentives for reducing energy consumption.

Financial incentives target the large upfront investments costs, a potential barrier for the uptake of energy efficiency measures, promoting energy efficiency investments through subsidies such as direct payments, tax rebates, grants and loans. Often, the support can be used to facilitate the purchase of specific products and support certain technologies (Galarraga et al., 2016; Bertoldi et al., 2013). Although beneficial and effective, examples from the literature show that financial incentives can lead to rebound effect (i.e. the lower cost of a product might increase the quantities purchased and, consequently, increase final energy consumption, (Galarraga et al., 2013)) and can be exploited by free-riders (i.e. end-users using the financial programs to finance their investments, although they had already planned to invest without any support, (Grösche and Vance, 2009)).

Regulatory measures usually take the form of codes and standards, such as building codes or minimum energy performance standards for appliances. Such policies act both on the supply and demand side: enforcing the producer to deliver energy efficient solutions in line with the standards and guiding the consumer providing indications on specific investments to reduce energy consumption (Filippini et al., 2014).

Non-regulatory measures includes voluntary agreements, defined as *"tailor-made negotiated covenants between the public authorities and individual firms or groups of firms which include targets and timetables for action aimed at improving energy efficiency or reducing GHG emissions and define rewards and penalties"* (Rezessy and Bertoldi, 2011). As negotiations between singular household and authorities can be challenging, these policies mostly target firms in the industrial sector. Examples from the literature show that such agreements can have an impact on the firm's investment behaviour, although they usually come with high administrative costs (Johannsen, 2002).

Last, *information-and-feedback* policies work through information campaigns, certificates, labels, audits or feedback measures to reach out directly the end-users, as often the suboptimal investment levels in energy savings measures are related with lack of information or improper energy use behaviour (Baldini et al., 2018).

In the journal papers presented in Part II, different policies frameworks are discussed in relation to the topic; proposing, when opportune, suggestions for improvements in light of the results from the empirical studies. For instance, in **Paper 3** we focus on information-and-feedback policies in relation to the adoption of household appliances, while in **Paper 4** we discuss about financial incentives and regulatory measures in relation to heat savings in the residential sector.

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Chapter 3

Methods

The investigation on the adoption of attractive energy savings interventions comes with challenges. The nature of the challenges can be diverse and can relate to different aspects involved. For instance, one could question on which bases is attractiveness assessed: is it economical (e.g., the cheapest option), or is it maybe environmental (e.g., the option saving more energy, regardless the costs)? Also, one could discuss for whom energy savings can be attractive: is it for personal (private) advantage, or is it maybe from a socioeconomic perspective? The scope can then extend to a broader perspective, questioning for instance if the choice of a particular saving measure is going to make an impact on the energy systems or it is irrelevant. Or one could question what are the reasons for which, in spite of the availability, energy saving potentials are not exploited completely; and as a consequence, explore which kind of changes in personal characteristics, support or technologies are required, to exploit better energy savings potentials.

On the bases of methodologies reflecting the logic behind these queries, models can serve as tools to provide suggestions on how to overcome challenges. The foundations for the thesis work are mostly bottom-up engineering-based, as the focus is to investigate on technical saving options and their impact on energy systems. Thereafter, we include additional economic and behavioural details, developing a broader approach and providing a more complete overview of the most efficient combination of savings and technologies.

In light of the discussion reported in Section 2.3, the main methodologies employed are: energy systems, consumer choice modelling and net present value of cash flows. The following sections provide the theoretical framework behind each methodology.

3.1 Energy systems modelling

The field of energy systems develops quantitative methods for performing energy systems analyses. One method commonly applied is energy systems modelling where, through a mathematical formulation describing the characteristics of the energy system, researchers can assess the optimal operation and structure of the energy system, e.g., based on the objective of cost minimisation.

On a Danish context, the literature suggests that several existing energy systems models can handle various aspects of energy systems analysis. Such models includes different functionalities and range from e.g., the operational model EnergyPLAN (Aalborg University, 2018), over the investment and operational models TIMES (ETSAP, 2018) and Balmorel (Balmorel, 2018), to the stochastic operational model Wilmar (Risø National Laboratory, 2008). From a broader international perspective, researchers employ other tools, such as the integrated energy systems simulation model National Energy Modelling System (NEMS) (Energy Information Administration, 2009), the ModUlar energy systems Simulation Environment (MUSE) (Imperial College London, 2018) or the integrated energy-economy equilibrium model CIMS (Rivers and Jaccard, 2006).

The tool selected for energy systems analysis is Balmorel, a model well suited for assessing the impact of savings in the energy system as it can optimise the system on an hourly level, minimising total system costs including investments.

Balmorel is a bottom-up, partial equilibrium, energy systems model which finds optimal economic dispatch and, optionally, long-term investment planning for power and heat sources, storage devices and transmission lines in energy systems. The optimal dispatch of generating units is determined minimising total operation costs given an inelastic energy demand, subject to restrictions on e.g., capacity generation or transmission. The model has different operating modes, allowing simulations considering e.g., short-term dispatch only or short-term dispatch and long-term investments planning.

A general formulation of the economic dispatch model with capacity investments for power and heat technologies corresponds to:

$$\text{Min:} \quad z = \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}^P} a_i p_{it} + \sum_{t \in \mathcal{T}} \sum_{i \in \mathcal{I}^{HO}} a_i q_{it} + \sum_{i \in \mathcal{I}^P} b_i \, p_i^{max} + \sum_{i \in \mathcal{I}^{HO}} b_i q_i^{max} \tag{3.1}$$

$$\text{s.t.} \quad p_{it} \leq p_i^{\max}, \qquad \forall i \in \mathcal{I}^P, t \in \mathcal{T} \tag{3.2}$$

$$q_{it} \leq q_i^{\max}, \qquad \forall i \in \mathcal{I}^{HO}, t \in \mathcal{T} \tag{3.3}$$

$$q_{it} = \delta_i p_{it}, \qquad \forall i \in \mathcal{I}^{CHP}, t \in \mathcal{T} \tag{3.4}$$

$$\sum_{i \in \mathcal{I}^P} p_{it} = d_t^E, \qquad \forall t \in \mathcal{T} \tag{3.5}$$

$$\sum_{i \in \mathcal{I}^H} q_{it} = d_t^H, \qquad \forall t \in \mathcal{T} \tag{3.6}$$

$$p_{it} \geq 0, \qquad \forall i \in \mathcal{I}^P, t \in \mathcal{T} \tag{3.7}$$

$$q_{it} \geq 0, \qquad \forall i \in \mathcal{I}^{HO}, t \in \mathcal{T} \tag{3.8}$$

$$p_i^{max} \geq 0, \qquad \forall i \in \mathcal{I}^P \tag{3.9}$$

$$q_i^{max} \geq 0, \qquad \forall i \in \mathcal{I}^{HO} \tag{3.10}$$

where $\mathcal{I}^P : \mathcal{I}^{PO} \bigcup \mathcal{I}^{CHP}$ is the set of power-producing plants (^{P}), composed by technologies producing power only ($\mathcal{I}^{PO}$) or combined heat and power ($\mathcal{I}^{CHP}$) and $\mathcal{I}^H : \mathcal{I}^{HO} \bigcup \mathcal{I}^{CHP}$ is the set of heat-producing plants (^{H}), composed by technologies producing heat only ($\mathcal{I}^{HO}$) or combined heat and power ($\mathcal{I}^{CHP}$).

Eq.(3.1) represents the objective function, set as minimisation of the total system costs (z), and includes two components. The first considers costs a_i associated with power (p_{it}) and heat production (q_{it}); the second considers investment costs b_i in relation to the capacity level (p_i^{max}, q_i^{max}) for each technology i. The production costs a_i include fuel (a_i^{fuel}), emission (a_i^{emis}) and variable operation and maintenance costs ($a_i^{O\&M}$) according to:

$$a_i = a_i^{O\&M} + \frac{a_i^{fuel} + a_i^{emis} \cdot p_i^{emis}}{\eta_i^{fuel}}, \tag{3.11}$$

where p_i^{emis} is the emission factor (e.g., $tonCO_2/MWh$) and $\eta_i^{fuel} \in [0, 1]$ is the fuel efficiency.

Eqs.(3.2)-(3.3) limit the power and heat production at every time step t according to the capacity installed, while Eq.(3.4) relates the generation of heat and power with the heat-to-power ratio δ_i for combined heat-and-power plants (assuming a back-pressure plant). Eqs.(3.5)-(3.6) ensure that the supply and demand of electricity (d_t^E) and heat (d_t^H) are balanced in all the time periods $t \in \mathcal{T}$. Last, Eqs.(3.7)-(3.10) ensure that energy production and capacities are positive variables.

The simplified formulation reported in Eqs.(3.1)-(3.10) mirrors Balmorel's structure. In Balmorel, the objective function minimise optimally the total system costs. Details about technical, physical and regulatory aspects are included in the model formulation as constraints, and allow an evaluation from an economical or environmental (e.g., which system configuration given caps on CO_2 emissions) perspective (Wiese et al., 2018). The base version of Balmorel is supplied with add-ons (namely, extensions of the model), which allow to extend the model code and provide additional functionalities, such as innovative technologies, electric vehicles or policy frameworks. Although useful, some add-ons can heavily influence the computational time (e.g., when considering integer problems), hence requiring a careful choice according to the research questions under investigation.

In line with this traditional code-structure development, part of the thesis work takes the shape of an add-on for Balmorel, including a method to reflect investments in energy savings. As the model presents already a strong description and representation of energy technologies (including renewables) from the supply side, the modelling efforts focus on the representation of energy savings investments and on specifics about energy demand.

3.2 Cost-effective savings investments

3.2.1 Energy systems perspective

The energy saving investments investigated in the thesis mostly concerns two energy commodities: heat and electricity. From an energy systems modelling perspective, investments in energy saving measures imply an alteration of the code-structure of Balmorel, according to the area of influence (i.e. if they save electricity or heat). Following the general formulation reported in Eqs.(3.1)-(3.10), investments in saving measures impact:

Objective function The choice of an investment depends on its economical value, i.e. how much it costs in regard to the existing supply options available. Hence investments expenses are added to the objective function of the model according to:

$$\text{Min:} \quad z = SysCost + \sum_{j \in \mathcal{J}} c_j^a \tag{3.12}$$

where $\mathcal{J}$ is the set of the saving measures j and $SysCost$ is the original objective function in Balmorel representing the total costs of the energy system. The annuitised investment cost c_j^a is calculated as in Eq.(3.13), where c_j is the investment cost, r the discount rate and L_j the lifetime of the measure[1].

$$c_j^a = c_j \frac{r}{1-(1+r)^{-L_j}} \tag{3.13}$$

[1]As in the thesis we mostly deal with small size investments, e.g. household appliances, we assume no O&M costs associated with their use.

Energy supply The aim of investing in energy saving measures is to reduce the energy demand through a cost-effective investment. Hence, savings impact the energy balance demand according to:

$$\text{(energy supply at } t) = \quad d_t \left(1 + \frac{\sum_{j \in \mathcal{J}} D_j}{D} \frac{\sum_{j \in \mathcal{J}} \xi_{jt} \beta_j}{\sum_{j \in \mathcal{J}} \xi_{jt}}\right) - \sum_{j \in \mathcal{J}} \xi_{jt}. \tag{3.14}$$

In Eq.(3.14), the energy demand d_t is decreased according to ξ_{jt}, which represents the hourly value of energy savings from the measure j (i.e. how much energy can the measure reduce at the time t). Eventual increases in energy demand due to rebound effect (intended as a greater use of energy as a consequence of the cheaper service available and/or economic gains achieved after the investment) are considered in the summing term among parenthesis, where the coefficient β_j represents the magnitude of the rebound (%) linked to the measure j, D represents the total demand of the energy system and D_j the total demand of measure j. The method can be applied independently to the electricity or heat balance equations, Eqs.(3.5)-(3.6), according to the target of the saving measure.

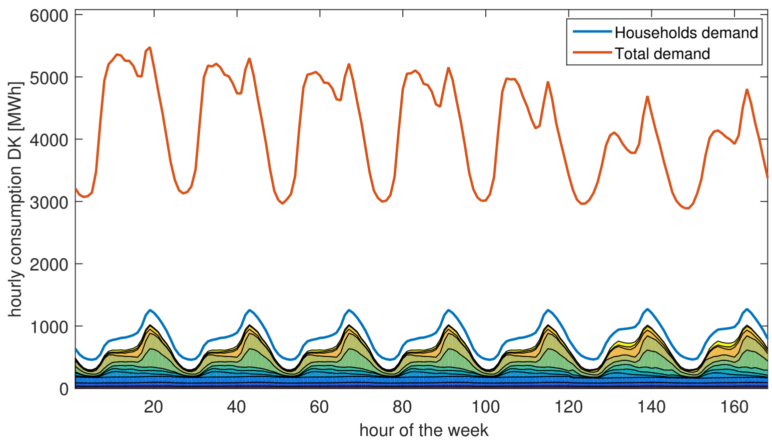

Figure 3.1: Aggregated profile of 11 household appliances compared to total household and energy system electricity demand, during a sample week.

Differentiation of energy demand As energy savings are considered in the framework of an energy systems model optimising operation and dispatch of technologies on an hourly scale, the analyses performed can provide indications about the properties of energy saved at different hours over a year. Also, the level of optimal energy saving investments can be the affected by changes in the energy supply side which, in turn, can be influenced by technical or regulatory aspects implemented in the model. To this end, to investigate on the interactions of additional energy savings in an optimisation framework of the heat and power sector at an hourly scale, it can be useful to improve the representation of the energy demand on a temporal scale, considering sectoral and end-use specifics. For instance, reporting the hourly consumption profile of household appliances in the residential sector can ease the analysis of impact, at system scale, of varying the energy efficiency of the same appliances.

Thereby, during the studies we enhance the representation of electricity and heat consumption demands available from Balmorel, developing temporal profiles of consumption tailored to end-uses. As an example, Figure 3.1 shows how the aggregated profile of a set of household appliances contributes to the total residential electricity demand of households and of all sectors in Denmark.

By reporting a fundamentally different representation of the demand in the energy systems model selected, focusing on the residential and industrial sector, we aim at enhancing the quality of the analyses and easing the study of the interaction and impact of energy savings on the energy systems at an hourly scale.

3.2.2 Private consumer perspective

The details involved in the choice of a cost-effective saving measure can vary between the energy systems and the private perspective. From the supply side, energy systems often display a broader range of options competing with the investment, while for private consumer it is often a discrete choice (i.e. either invest or continue business-as-usual). Moreover, energy systems and private consumers are subject to different conditions in regard to energy prices: analyses performed from energy systems perspective are based on the so-called "socioeconomic approach", neglecting the contribution of taxes and assuming low discount rates (i.e. less capital exposure to the risk of investments). On the other hand, private consumers pay taxes on energy and are more exposed to the initial investment costs, requiring higher values of discount rates; namely "private-economic approach". As a consequence, the evaluation of cost-effective investments in energy saving measures from a private perspective requires a different approach.

We start with the assumption of a consumer informed and acting rationally. The consumer would compare the investment cost of a saving measure c_j with the expected economic saving resulting from the consumption reduction throughout the lifetime, and would undertake an investment in case of positive Net Present Value (NPV) of cash flows according to:

$$NPV_j = -c_j + \left[\sum_{y=1}^{L_j} \frac{\alpha_y}{(1+r)^{y-1}} \left(\sum_{t \in \mathcal{T}} p_t^c \, \xi_{jt} \right) \right] \tag{3.15}$$

with p_t^c the price related with energy consumption, being this electricity, heat or any other commodity under investigation. The price can be time dependent (i.e. varying at every time unit t) or fixed (i.e. fixed value for every time unit). The first assumption can hold for electricity as in the future, with the rolling out of smart meters, time-dependent tariffs are expected to be common for electricity consumption; fixed-tariffs can be more easily employed for heat consumption (e.g., long term contracts).

Eq.(3.15) represents the trade-off between investment cost and cumulative annual saving. The expression inside parentheses represents the economic saving for the current year, calculated by multiplying the energy price with the consumption reduction achieved for every measure ξ_{jt} and summing over the temporal horizon considered. The expression is then summed over a number of years corresponding to the lifetime of the measure L_j, discounted, and multiplied by a factor α_y indicating the expected change (increase or decrease) of energy prices for year y.

3.3 Consumer choice modelling

The method presented in Eq.(3.15) is based on the assumption that the consumer is thinking rationally and is well informed about energy consumption, prices and savings. In practice, however, consumers do not act in a fully economical rational way, as there are factors that might influence the investment decision. The relation between the consumer choice (i.e. the investment) and consumer characteristics (e.g., socioeconomic factors such as age, education, income or behavioural components) can be assessed through consumer choice models, on the bases of observations (e.g., survey data).

Among the methods in the literature, in line with the discussion in Section 2.3.2, we select a discrete choice model based on logistic regression. The consumer investment (choice) can be generally formulated as:

$$y^* = x\beta + \varepsilon \tag{3.16}$$

where y^* is a latent variable capturing consumer's preferences in regard to the choice (i.e. the difference between the marginal benefit and the marginal cost of investing in the measure, also known as net utility), $X = [X_1, \ldots, X_n]$ represents the vector of explanatory variables under investigation (e.g., age, income, type of house, behavioural characteristics, etc.), $\beta = [\beta_0, \ldots, \beta_n]$ the weight vector to estimate and ε is the error term, which captures the impact of all unobserved factors that affect the consumer's choice. Normally, researchers cannot observe the preference directly (i.e. the "utility" that a consumer gains by making that choice), but they can examine the choice and some attributes of the decision-maker. Hence, generally, the consumer choice can be inferred from the data available according to a decision rule:

$$y = 0 \quad if \quad y^* < 0 \tag{3.17}$$

$$y = 1 \quad if \quad y^* \geq 0 \tag{3.18}$$

meaning that the consumer invests in the good ($y = 1$) if the marginal benefit of investment is larger or equal than the marginal costs. Otherwise, it does not invest ($y = 0$). Consequently, the model can be seen as a description of the relation between the explanatory variables and the outcome of a choice, without reference to exactly how the choice is made (Train, 2002). To estimate the model, the weights β are fitted through logistic regression, based on data from the survey analysed, via logit maximum likelihood function, according to:

$$\begin{aligned}&\mathrm{logit}(P(y = 1 \,|\, X_1 = x_1, ..., X_n = x_n))\\ &= \log \frac{P(y = 1 \,|\, X_1 = x_1, ..., X_n = x_n)}{1 - P(y = 1 \,|\, X_1 = x_1, ..., X_n = x_n)}\\ &= \beta_0 + \beta_1 x_1 + ... + \beta_n x_n.\end{aligned} \tag{3.19}$$

Then, given the estimates $\hat{\beta} = [\hat{\beta}_0, \ldots, \hat{\beta}_n]$ and the characteristics of a consumer $x = [x_1, \ldots, x_n]$, the resulting predicted joint-probability π of investing in an energy saving measure, or the probability that $y = 1$, is computed as:

$$\begin{aligned}\pi &= P(y = 1|X_1 = x_1, ..., X_n = x_n)\\ &= \frac{\exp(\hat{\beta}_0 + \hat{\beta}_1 x_1 + ... + \hat{\beta}_n x_n)}{1 + \exp(\hat{\beta}_0 + \hat{\beta}_1 x_1 + ... + \hat{\beta}_n x_n)}.\end{aligned} \tag{3.20}$$

The merit of such modelling framework is the ability to empirically test the predictive strength of the explanatory variables, hence identifying relevant consumer characteristics and quantifying their impact on the consumer choice.

Purchase probabilities[2] determined through the consumer choice model can be combined with the rational economical approach, to achieve more realistic estimations on the uptake of energy saving measures by consumers. The results from the consumer choice model could also be integrated in the framework of the selected energy systems model, to optimise the energy systems while considering consumer's preferences.

[2]The change in predicted probability of investment associated with variations in the explanatory variables.

3.4 Considerations on the methodologies adopted

Before the exploration of the contributions, it is worth to highlight a few considerations in regard to the benefits and drawbacks of the methodologies adopted. Models are an approximation of the reality or rather a rational way of representing it[3]. As such, model can rarely give a precise, exact and doubtless answer, but rather provide indications about how certain details can lead to particular outcomes in regard to the research question.

Hypothetically, the greater the number of aspects involved in the designing of a method, the closer the outcomes can be to the reality. Nonetheless this comes with challenges as, although beneficial, larger models can require excessive resources (e.g., computational time or calculator's performances) and become slow. Also, the broader the model, the larger the risk that details related to the methodologies fade, eventually transforming the model in a black box where important aspects are obscured. Hence, it is essential to find a compromise between model approximation, simulation time and transparency. In line with these considerations, the following paragraphs focuses on benefits and drawbacks of each methodology.

3.4.1 Energy systems modelling

Solutions from the energy systems model Balmorel provide indications about the optimal configuration of the energy system under study, given the set of constraints imposed. According to the objective function of the mathematical formulation in Eq.(3.1), the solution of the model can be interpreted as the least-cost solution to satisfy the energy demand, operating an asset available and (if considered) investing in new technologies. During the optimisation process, the models considers a wide range of technology characteristics and hourly temporal profiles of energy consumption, thus allowing to perform detailed and thorough analyses. Yet, Balmorel is based on a set of assumptions that, although inevitable, undermine the perfect representation of the energy systems operating principles in the reality. Three are the most significant assumptions:

1. *economic rationality*: the model does not include strategic behaviour of energy producers, thus optimising the operation of the plants according to the marginal costs of production based on technical characteristics of the plants. In the reality, energy producers bid strategically in the energy market according to a specific behaviour, most often aiming at profit maximisation;

[3] Intended as a representation in which all actors behave as robot-like experts, following a set of pre-defined rules (See e.g., Thaler (1981)).

2. *perfect market*: from a broader perspective, the optimisation process of the model mirrors the functioning of a perfectly competitive market, in which each participant behaves optimally according to the rules. As the real energy market shows quite some imperfections compared to these assumptions, such rendering distance the model from reality;

3. *perfect foresight*: Balmorel is a deterministic model, hence assumes perfect foresight on specific exogenous data such as profile of intermittent renewable generation, import/export, lines or plants faults, future energy demand or fuel prices. While this assumption could be realistic when performing ex-post analyses (e.g., What would have happened, on the last year's energy system, if we had added more energy savings?), it surely has a relevant influence on simulations based on future years.

Summing up, Balmorel assumes a central planner which, based on rich and thorough systems characteristics, optimise an asset of existing and new technologies. The optimisation process is based on assumptions that reflect ideal circumstances. As such, outcomes from the model simulations are valuable and informative, but should be intended more as general recommendations and indications rather than an doubtless description of how the system will react in case of external modifications.

3.4.2 Cost-effective savings investments

In the framework of energy savings investments, the thesis focuses respectively on energy systems and private consumer perspective. For both approaches we report a mathematical formulation reflecting the process behind a cost-effective saving investment. The methodologies have been tested on case studies, reported in the journal papers, proving that the methods developed can facilitate the understanding of the investment process in energy savings. Nonetheless, the outcomes are based upon primary assumption linked with the methodologies. Among those, few are worth some remarks:

1. *investments costs (full vs marginal)*: in Eq.(3.12), c^a_j represent the annuitised investment costs. When investigating on the costs for savings opportunities, the literature considers two approaches: full or marginal investment costs (see e.g., Wada et al. (2012) or Zvingilaite (2013); Zvingilaite and Balyk (2014); Zvingilaite and Klinge Jacobsen (2015)). The first approach considers the full investment cost of the measures. The second approach is based on the assumption that the investment is going to be performed anyway; the cost considered is then the additional cost of investing in a measure with higher saving potentials, with regard to the cost of

a baseline measure providing the same service. For this case, the rational consideration on the choice of the appropriate measures would be "How much more is it worth to spend on an even more efficient measure, which can bring additional benefits and savings?". As an example in the household sector, assuming that a baseline refrigerator with efficiency class A has an average cost of EUR 650, and the most efficient class A^{+++} has an average cost of EUR 1000, then the marginal cost would be EUR 1000 - 650 = 350[4]. In the case study of **Paper 2** and **Paper 4**, we adopt the marginal investment cost approach, hence providing suggestions on an alternative, more efficient investment, that a consumer could perform.

2. *discount rate (private vs socioeconomic)*: when assessing the costs and long-term benefits of saving investments, discount rates hold a paramount role as they reflect the capital cost and expected rate of return of investments. Discount rates harmonise the present and future values of payments and income streams derived from investments through discounting, converting future incomes and outcomes into annualised costs at present value. Consequently, as highlighted in Eq.(3.13) and Eq.(3.15), the choice of discount rate highly influences the outcomes of economic assessment of energy saving measures.

   During the thesis, we consider both socioeconomic and private discount rates: the former relates to evaluations of total costs and benefits in energy systems, from a societal perspective; the latter refers to investment decision making, based on NPV calculations, reflecting the expected return of a private investor (being this a household, commercial or industrial consumer). Socioeconomic discount rates often have lower values than private, as the social perspective should be reflected by risk-free discount rate declining over long time horizons; consequently, discount rate values typically range from 1 % - 7 % (Steinbach and Staniaszek, 2015; Hermelink and De Jager, 2015). On the other hand, as the private investment is related with the concept of expected rate of return (thus a risk-aversion attitude), private discount rates are higher. As they are linked with economic expectations, discount rate values should first be different between commercial-industrial (6%-15%) and household (3%-6%) investors (Steinbach and Staniaszek, 2015; Hermelink and De Jager, 2015). Furthermore, as the individual socioeconomic condition can impact the decision on investment, it would be coherent[5] to assume heterogeneous discount rates with regard to risk attitude (i.e. risk taker or risk averse) and other characteristics such as socioeconomic parameters of individual consumer (e.g., age, income).

[4] Clarification note: during the thesis we neither develop costs, nor gross or net saving potentials, but we rely on previous analyses and/or market observations. Only in **Paper 4** we compute our own marginal costs, based on the work from Brøgger and Wittchen (2018).

[5] Provided that data/indications allowing such differentiation are available.

When evaluating investments according methodologies based on NPV of cash flows, discount rates are often used as proxies to include elements about non-economic barriers and bounded rationality, increasing proportionally the values. However, this approach is not entirely correct: firstly because it assumes that the investor performs a rational evaluation of economic efficiency, according to Eq.(3.15); second because if other non-economical barriers are considered relevant for the case study, a pure economic evaluation does not mirror correctly the investor decision making process. Hence, unless no other options are available, higher discount rates are not entirely appropriate. To this end, to simulate real-world investment decisions, it is more suitable to integrate choice models with behavioural components (e.g., logit) in energy systems optimisation, considering explicitly individual decision criteria and barriers for the uptake of energy savings (Steinbach et al., 2013).

Summing up, the choice of discount rates can lead to over or under-estimation of the most cost-efficient savings, hence undermining future projections on the role of energy savings towards the future. Sensitivities on the range of discount rates can help to capture the influence of this parameter on the overall results. On the bases of these considerations, in **Paper 2**, **Paper 3** and **Paper 4** we link economical, non-economical and optimisation methodologies to perform an evaluation of cost-efficient saving measures from a broader perspective. Also, we include an analysis about the impact, on the results, of sensitivity in the discount rate.

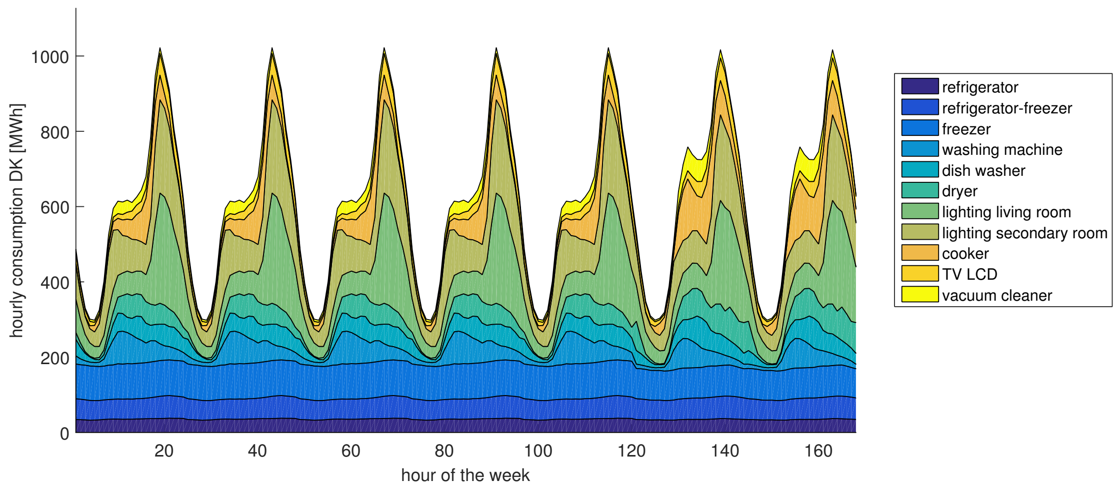

Figure 3.2: Electricity consumption profile during a sample week of 11 household appliances.

3. <u>*temporal profile of savings*</u>: in line with the approach reported in Eq.(3.14), ξ_{jt}, represents the hourly value of energy savings from the measure j (i.e. how much energy can the measure reduce at the time t). The formulation implicitly assumes the knowledge of "energy saving profiles", a concept that could be perceived as abstract. During the thesis we generate saving profiles linking the absolute value of savings of a measure with its relative hourly profile of consumption.

For instance, Figure 3.2 reports hourly profiles of consumption for a set of household appliances, on a sample week in Denmark. Let's focus on a single appliance, e.g. dryer. Assuming that the saving potential for the appliance is represented by the difference between the consumption of the current dryer (e.g., 300 kWh/year) and a more efficient dryer with the same characteristics (e.g., 180 kWh/year), then the absolute savings will be 300 - 180 = 120 kWh/year. If we relate the absolute savings (kWh) with the relative profile of consumption of the appliance (% consumption/hour), we can compute the energy saving profile (kWh/h). In other words, we consider that the saving is spread over the whole year and applies with the same percentage across the consumption profile of the appliance. If the investment in that particular appliance is performed, the new hourly profile of consumption is reduced accordingly.

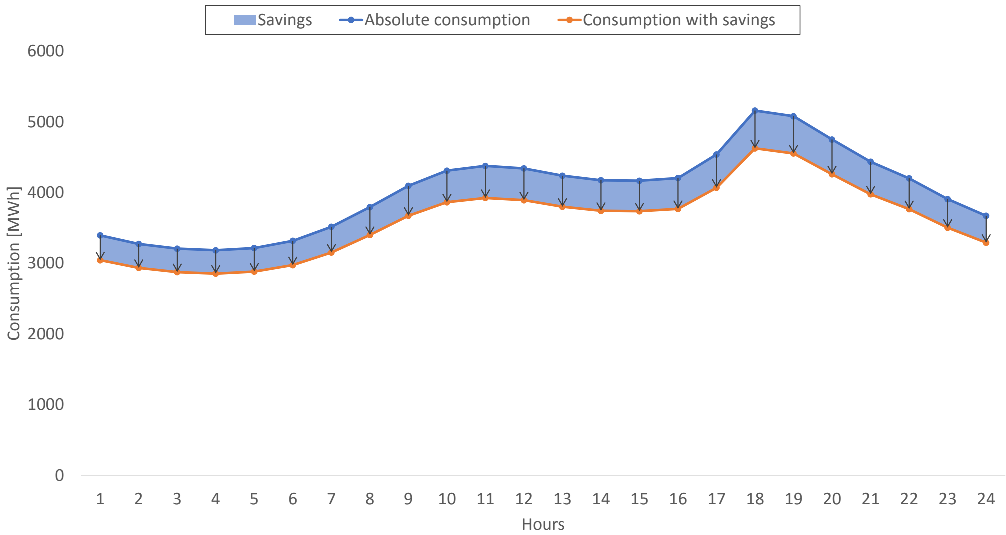

Figure 3.3: Effect of savings on electricity demand; sample data from (NordPool Market, 2018).

Figure 3.3 provides a visual representation of the logic, where the blue line is the hourly profile of consumption from the appliance, the blue area represent the absolute reduction due to savings and the red line the new hourly profile of consumption after an investment in a more efficient dryer. The approach is particularly useful as it allows to focus on the contribution of savings on a temporal scale and analyse their effect within the energy systems, while performing optimisation on an hourly level. Furthermore, as savings profiles differ between end-uses and sectors, a deeper level of investigation on energy savings similar to the one illustrated, combined with the details on the interaction between the power and heat technologies at hourly scale, can provide a more thorough perspective on the effects of savings across sectors in energy systems.

3.4.3 Consumer choice modelling

The use of a discrete choice model, to investigate on the behavioural process that leads to a consumer's choice, is common use in the literature. Other studies focusing on the description of consumer's characteristics in relation to investments in energy savings (for instance Ameli and Brandt (2015); Mills and Schleich (2010)), employed a similar methodology. However, as the researchers usually cannot observe the factors that lead to the consumer choice, the use of such model can suggest the relation between the explanatory variables (i.e. consumer characteristics) and the choice, rather than explain exactly how the choice is made (i.e. the process itself).

During our research, in **Paper 3** we employed answers from a survey in regard to behavioural aspects (such as, "How full do you fill your clothes/washing machine on a normal use?" or "Do you turn off the power socket during the night?") to compute what we defined "energy efficiency index" (EE index). By incorporating unique responses about energy consciousness and intent to save energy, we developed an explanatory variable accounting for the "non measurable factors" in relation to the decision of investing in an energy saving measure. Furthermore we also investigated on the contribution of "energy consciousness behavioural aspects" to the final score of the EE index, thus highlighting what matter the most and, in turn, what can increase the probability of investments given certain actions performed.

In this way, we attempt to quantify probability of investments given consumer behaviours and, although simple, the approach provides a good indication about how particular behavioural aspects can relate to the probability of investments, allowing to target these aspects with policies. Last, other methodologies could have been employed to draw observations about investment propensity in saving measures; however to the best of our knowledge and based on the literature investigated, the discrete choice model employed was the most appropriate for the analysis.

3.5 Methods and case studies

In relation to the benefits and drawbacks of the methodologies described, the thesis aims at combining various methods, to compensate for the limitations of one approach or the other. To this end, during the thesis we mix optimisation methods with consumer preferences and behavioural components, focusing on different sectors, providing a broader and more complete view of the most efficient combination of savings and technologies. Figure 3.4 provides an overview of the methodologies adopted in the different papers.

On the basis of the energy systems model Balmorel, in **Paper 2** we develop the core-code to consider investments in energy saving measures (specifically, household appliances) from an energy systems perspective, extending the representation of temporal profiles of electricity demand. Furthermore, in **Paper 5** we add new functionalities in relation to operational and investment aspects of the industrial sector, including energy saving measures and profiles of consumption. To examine attractive investments from a private perspective and consider taxes and higher energy prices, in **Paper 2** and **Paper 4** we investigate further on cost-effective investments in regard to electricity and heat savings. To explore the non-rational elements driving a consumer to invest in energy saving measures, in **Paper 2** we consider the influence of behavioural aspects. Furthermore, with a different extent, in **Paper 4** we consider the generic influence of residents behaviour in regard to realisable energy saving potentials, in the residential sector. Last, in **Paper 3**, on the bases of an empirical analysis, we validate and extend the considerations about the influence on socioeconomic and behavioural factors for purchasing energy efficient household appliances, based on a consumer choice model.

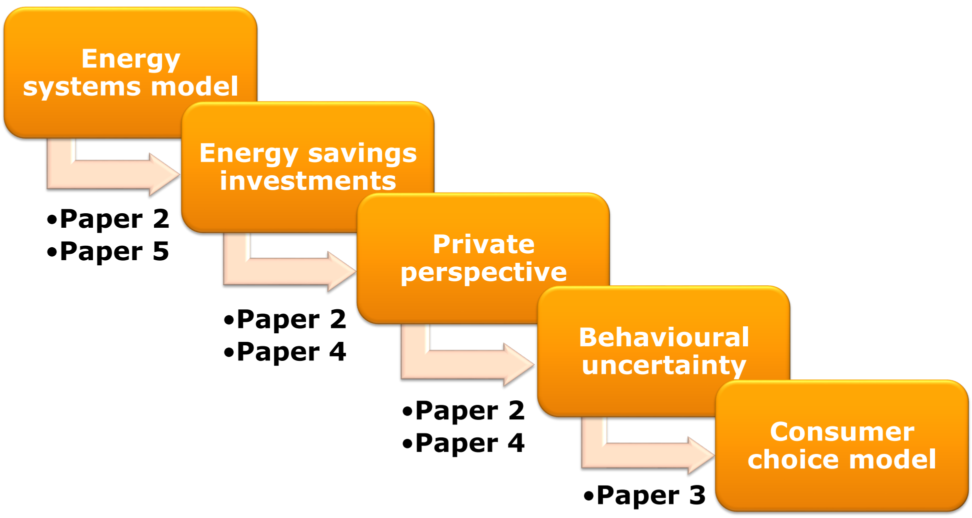

Figure 3.4: Visual representation of methodologies applied in the different papers.

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Chapter 4

Contributions

In light of the approaches and methodologies presented, the following chapter reports an overview of the scientific contributions from the academic journal papers developed in the framework of the PhD project. Table 4.1 reports an overview of the dissemination activities related with the work performed.

Table 4.1: Contributions of the work performed.

		Dissemination activities	
Paper	Journal	Type	Conference
1	IEEExplore	Abstract	• *ENERDAY16* - 11th Conference on Energy Economics and Technology, Dresden, Germany
		Conference paper	• *EEM16* - 13th International Conference on the European Electricity Markets, Porto, Portugal
2	Energy Efficiency	Peer-reviewed extended abstract	• *BEHAVE 2016* - 4th Conference on Behaviour & Energy Efficiency, Coimbra, Portugal
3	Energy Policy	Conference paper	• *EEDAL 2017* - 9th International Conference on Energy Efficiency in Domestic Appliances and Lighting, Irvine, USA
		Peer-reviewed extended abstract	• *IAEE 2017* - 40th Conference International Association for Energy Economics, Singapore
4	Applied Energy (prepared for)	Conference paper	• *WSED 2019* - World Sustainable Energy Days 2019, Wels, Austria
5	Journal of Cleaner production	Conference paper	• *SDEWES 17* - 12th Conference on Sustainable Development of Energy, Water and Environment Systems, Dubrovnik, Croatia

Paper 1 - Optimal trade-offs between Energy Efficiency improvements and additional Renewable Energy supply: A review of international experiences

As an introduction to the field in **Paper 1**, **Chapter II** we perform a literature review on international experiences investigating on the potential implementation of energy efficiency improvements (EE) in combination with additional renewable energy supply (RES) in energy systems, focusing on the different purposes and models employed.

At first, we review the tools adopted for the analyses, presenting and categorising the models according to characteristics, such as bottom-up/top-down model, partial/general equilibrium or static/dynamic model. We then scrutinise the studies aiming at (i) understand under which objectives researchers on the field perform analyses, (ii) inspect the tailored methodology employed, (iii) highlight the perspective while evaluating the results and (iv) discuss and reflects on the final findings.

We find that purposes can be gathered in three broad categories, being GHG/CO_2 mitigation options investigation, targets fulfilment study and analysis of policies and programs development. Almost all the studies follows the "system operation/investments-cost minimisation while adhering to constraints" approach, with policies objectives implemented as constraints on the different variables under investigation. The outcomes from the different studies point to similar conclusions and, among the most supported, include the following:

- synergies between RES and EE are commonly acknowledged, while co-optimised trade-offs modelling methods are still not well defined;
- attention must be paid to the rebound effect as it can reduce net savings (economic, energy and emissions);
- EE measures imply costs to overcome barriers, necessary to spread the knowledge, which can hinder their development;
- EE measures are the most cost-effective options for CO_2 reduction in energy systems;
- EE measures should be implemented first, RES after.

The conclusions from the review highlight that, in accordance with the methods employed, a path of integration between RES and EE measures exits; the challenge lays in coordinate support modelling approaches to achieve the desired result at the lowest cost. The outcomes of the study are relevant for (i) identify methods to analyse key questions linked to the scope of the PhD and (ii) as a guidance for decision makers, in the process of identifying a suitable analysis to investigate on optimal trade-offs between renewables and energy efficiency measures in energy systems, under different objectives.

Paper 2 - Modelling of electricity savings in the Danish households sector: from the energy system to the end-user

On the bases of the identified methods and models from the literature review, in **Paper 2**, **Chapter 7** we develop our own analysis, focusing on a specific part of the energy demand. The case study focuses on the value of investments in energy-efficient (i.e. high-labelled) household appliances and the impact on energy systems. In the current Danish residential sector, electricity consumption is mainly related to home appliances. Hence, at the moment of replacement, any investment in a more efficient device can reduce the residential demand and potentially lead to benefits, both in economic and energy terms. Also, as savings relates to the alternative available, there can be actors subject to different conditions (e.g., energy systems and end-user) interested in a different level of investments. Our research question is to identify the most cost-effective investments in household appliances, quantifying energy and economic savings from an energy systems and end-user perspective.

We consider a set of appliances constituting the majority of the electricity consumption in the Danish private household sector (e.g., refrigerator, freezer, dishwasher, washing machine, dryer), and collect data from multiple sources and suppliers to determine average characteristics, according to representative energy label classes. For the energy systems perspective we use Balmorel, a bottom-up energy systems model that optimise the operational and investment aspects of a typical energy system, considering the heat and power sector. To evaluate the most cost-effective savings solutions, we extend the model formulation to include endogenous investments in energy efficient household appliances, including hourly profiles of energy consumption and electricity savings for each measure. A saving investment is deem attractive if investing in improved energy efficiency can compete with the cost of electricity supply from existing or new power plants, under different assumptions. To include aspects about private consumer perspective and assess the impact of the consumer choices on the energy systems, we develop a method relating the cost-effective system and consumer investment decisions, by soft-linking Balmorel with a consumer investment model designed for the study.

The outcomes show different levels and diversified choice of investments among the system and private end-user approach, highlighting the effect of modelling different perspectives and the factors influencing the decision criteria for the two models. In particular, when compared to a business-as-usual energy scenario, the results show that an average end-user could enjoy economic benefits in the range of 30 - 40 € and could contribute between 0.43 - 0.46 % and 0.48 - 0.51 % to the reduction of Danish energy demand and CO_2 emissions, per year. From an energy systems perspective, the same energy and CO_2 emission savings could range between 0.38 - 0.49 % and 0.34 - 0.87 % respectively. The analysis also reveals an impact from the optimal investments decisions not only on the Danish power system but also on the surrounding countries, highlighting that decision of a single consumer can contribute to the diversification and transformation of energy systems. The paper enriches the existing literature about energy efficiency modelling in households, quantifying economic and energy savings from an energy systems and private perspective and providing insights on the trade-off between investments costs and resulting energy savings. Although the outcomes relate to the Danish case study, the methodology proposed can be employed to different countries or geographical regions, given the availability of data needed to model the energy systems as well as investments in household appliances.

Paper 3 - The impact of socioeconomic and behavioural factors for purchasing energy efficient household appliances: A case study for Denmark

The consumer investment model presented in Paper 2 is elementary, as the primary focus of the study is on energy systems and on the link between energy systems and consumer's investments. The model is a simple tool based on linear probability, where investment choices are considered as rational decisions based on positive net present value of cash flows and are partly influenced by generic behaviour uncertainty linked to income levels. Nonetheless there can be other factors characterising investment probabilities in energy efficient appliances, such as socioeconomic or behavioural. Consequently, on the bases of empirical survey data, in **Paper 3**, **Chapter 8** we investigate further on influential factors behind Danish consumer choice of energy efficient household appliance, exploring the effect of behavioural aspects, related to energy use and savings, on the purchase of the same household appliances.

To estimate consumer propensities for investment in a new, highest-labelled household appliance, we use a logistic regression model over a set of socioeconomic, demographic and behavioural variables, based on results of a survey performed by the Danish Energy Agency. Then, we compute a behavioural variable, namely energy efficiency index (EE-index), gathering characteristics about consumer energy end-use behaviours. We also compute propensity curves, to investigate changes in predicted probabilities for variations in the explanatory variables. Based on the outcomes, we identify variables and daily energy end-use actions that policy could target, to foster energy efficient behaviours and increase the uptake of EE appliances in the residential sector.

The paper presents methodological and empirical contributions, resulting in useful findings. On the methodological side, the contributions of the paper consist of (i) the construction of an EE-index that gathers and synthesises a rich set of consumer behavioural

characteristics and daily actions regarding energy end-use and energy savings, and (ii) the integration of such index in a consumer choice model to study the joint effect of socioeconomic, demographic, and behavioural variables on consumers energy efficiency investment choices. Furthermore, unlike previous studies, (iii) we perform an extensive investigation of a behavioural index through correlation matrices and by examining interrelations between its constituent parts. On the practical side, we find from our statistical results that socioeconomic and behavioural characteristics are highly significant when explaining the choice of purchasing EE appliances. Specifically, income, housing type, quantity of inhabitants, age, and end-use behaviour are predictors for choosing energy efficient appliances, with EE-index and housing type being the strongest of these predictors while income is weaker. Furthermore, the analysis of the EE-index identifies that specific daily actions can be related with investment in efficient household appliances.
By providing empirical results on the influence of both socioeconomic and behavioural variables on consumer choice, the paper narrows the knowledge gap on household energy consumption behaviour and on drivers of purchasing high-labelled household appliances.

Paper 4 - Cost-effectiveness of energy conservation measures in a Danish district heating system

In **Paper 4**, **Chapter 9** we investigate on attractive heat savings options for a sample of buildings, in the Danish district heating area of Aarhus. We evaluate cost-effectiveness options from a private end-user perspective, by comparing the investments with the cost of heat and we assess the cost-effectiveness of energy conservation measures (ECMs) in relation to the energy efficiency of the buildings, in terms of Energy Performance Certificates (EPC). Last, we study the effect on exposing the private consumer to different heat tariffs, in relation to a potential uptake of energy savings measures.

Using a building-physics based building stock energy model, and considering individual components in each building, we compute costs and values of *gross* energy saving potentials. To account for possible post-renovation demand related effects, we also compute *net* energy saving potentials. We evaluate the cost-effectiveness based on net present value of cash flows comparing investments with the cost of heat consumption. In other scenarios, we analyse changes in the current district heating tariff structure in order to make heat-cost components variable and we assess variations in the results according to different discount rates.

We find that total cost-effective potentials account for 9.3% and 1.9% of the current gross and net heat demand of the building stock. The low level of investments is in line with the level of heat prices in district heating areas, which is among the lowest compared to other options, for instance individual heating sources. The results highlight variations in the level of investments according to building characteristics and measures types: as expected, buildings with low energy performances (e.g. D-E-F-G) show greater investments compared to the others; roofs, external walls and floors are found to be the most attractive measures, while windows and mechanical ventilation systems are found to be the least. The results also show relevant sensitivity to variations in the values of the discount rates. Last, when all the cost components are made variable, we observe a considerable increase in the total cost-effective of investments, with specific ECMs distributed un-evenly among building EPCs categories. Investments in buildings with high EPCs are mostly linked to the subscription payment; for buildings with low EPCs, most of the investments are related to the consumption and capacity components. Although advantageous from a private investor perspective, such hypothetical heat-tariff structure can create implications at energy systems scale for the district heating (DH) companies. In this relation, we discuss potential implications, ultimately highlighting a synergistic effect between energy-savings and DH supply. By providing empirical results on cost-effectiveness of building-tailored heat saving measures in the residential sector, the paper highlights attractive residential energy savings and broadens the knowledge of heat-tariffs influence on energy saving investments. Moreover, the results provide indications about the distribution of cost-effective savings among buildings, according to given heterogeneous characteristics of the sample considered.

Paper 5 - Conceptual model of the industry sector in an energy system model: A case study for Denmark

In **Paper 5**, **Chapter 10** the focus moves from the residential to the industrial sector. In particular in this chapter we focus on the industry sector, characterised by a high share of emissions and an intense and diversified energy demand. Changes in the industry sector towards more sustainable alternatives include options such as efficiency interventions, fuel substitution, electrification and energy cascading[1]. Due to the interdependencies within energy systems, the application of such measures can influence the operation and transformation of energy systems. We observe that most of the bottom-up energy systems models represent and simulate industry in a simplistic way, neglecting the complexity of industrial processes and disregarding relevant details such as temperature heat levels, fuel use characteristics and temporal profiles of energy consumption (e.g., on an hourly scale). Consequently, analyses based on such models can misrepresent the impact of changes in the industry sector and can lead to misleading results, both in terms of policy design and energy systems operation and planning. Our research question is to identify structural

[1]Energy cascading is defined as the use of high quality heat from a source to be reused for other processes or for general heating.

characteristics of the industry sector and, on these bases, design a methodological approach mirroring operational aspects of the industrial processes in the framework of an energy systems model.

We develop the analysis based on a Danish structural case, investigating on details about industrial consumption in terms of end-use processes, heat temperature levels, geographical location and temporal profiles of energy consumption, and fossil fuel reduction options. To create a benchmark for analyses that can focus simultaneously on the impact of changes in the industry (e.g., energy efficiency, electrification, fuel substitution) and in the energy sector (e.g., renewables, energy efficiency) on a system wide scale, we develop a method reflecting operational details of the industry sector at hourly level and we integrate it in the energy systems model Balmorel.

The paper contributes with methods, useful for researchers, industrial institutions and policy makers. On the practical side, by mean of a Danish case study, the paper sheds light on particular characteristics of the industry sectors.
In particular, electricity, natural gas and district heating are found to dominate the total industrial energy consumption, while the relevance of consumption by end-uses varies according to the sector considered. The process of mapping the industrial energy consumption shows the relevance of the high geographical resolution, particularly when dealing with interconnections between commodities (e.g., heat and electricity) and end-uses, for instance about potential cases for energy cascading. The temporal profiles presented, which were found to vary according to the purposes (e.g., fuel consumption for process or space heat), stress the importance of using real data instead of constructed profiles, indicating situations that are particularly useful for studies on energy systems, such as drops in energy demand, seasonality of the profiles or weekly schedules. In this context, electrification is particularly relevant given its existing potential as it will enhance the industrial dependence from electricity use and, consequently, from the electricity generation sources of the energy system. The outcomes also show a potential applicability of energy cascading, electrification and fuel substitution for industrial processes, engaging elements and technologies interlinked within the energy system.
Although we do not quantify the impact of industrial changes in regard to e.g., energy savings, the methodology creates the foundation for analyses on tailored research questions according to more stringent policies capping CO_2 emission levels, exploiting the simultaneous optimisation of power, district heat and industry dispatches and characteristics. By providing a methodology with interlinked elements of industrial processes and tailored characteristics, the paper narrows the gap on modelling and representation of the industrial sector in bottom-up energy systems models.

Chapter 5

Summary and conclusions

The ongoing evolution of the energy sector, in line with a forecasted increase in global energy consumption, poses challenges on the energy demand and supply side. In this framework, the interdisciplinary research SAVE-E project, focusing on Danish cases, aims at examining what makes households and companies invest in energy saving solutions, combining potentials, barriers, incentives and strategies for implementing targeted improvements. To tackle these problems, the thesis leverage tools ranging from energy systems analysis to consumer choices, to design novel methodology and to seek results.

Following the definition of the research questions in the introduction, the elaboration on the multidisciplinary approaches involved in the field of energy savings, the overview of the methods adopted to investigate on cost-effective energy savings options and the highlights from the scientific contributions of the papers, this chapter concludes the dissertation emphasising the relevance of the findings and proposing future works.

5.1 Synopsis on research questions

At the beginning of the PhD thesis, we defined a series of broad and specific research questions, which we investigated upon throughout the work developed. We hereby report an interpretation of the results, focusing on the key points.
From a broader perspective, we aimed at:

1. **Understanding the additional value of modelling energy savings investments in bottom-up energy systems models.**
   Energy savings, in combination with renewable energy sources, can contribute to reach environmental targets. Technical potential savings, which differ among sectors and end-uses, should be realised in a cost-efficient way. To identify the least cost investments, potentials should be compared with the supply options available in the sector. To find the trade-off between a demand side with potential savings and a supply side with renewable options, investments in energy savings and in supply technologies should be optimised simultaneously. By means of the bottom-up, energy systems optimisation model Balmorel, during the thesis we enhanced the functionalities of the model to determine investments in attractive energy saving measures and assess the modelling value of the energy saved. In the innovative model design, the additional value of modelling energy savings investments is the possibility to identify, through an engineering-economic approach, cost-efficient saving potentials and perform thorough analyses of support-policies design.

2. **Investigating the additional benefits of modelling in details temporal profiles of energy savings and consumption, for the end-use sectors.**
   The bottom-up energy systems model selected optimise dispatch and investments of technologies on an hourly temporal scale. Hence, when considering investments in energy savings measures, these must be balanced by the real system cost and by the environmental value of saved energy (i.e., the specific type and environmental characteristics of saved energy). By developing and including temporal profiles of consumption for end-uses in various sectors and linking saving potentials, we incorporate in the model additional details about the properties of electricity saved at different hours over a year. On the bases of this enhanced model structure, we can study specific engineering-economic-policy aspects and actions, analysing changes on the demand and supply side, as a consequence of attractive saving investments, when performing energy systems analyses under different objectives.

3. **Exploring what are the modelling effects of using different types of methodologies while investigating on attractive energy savings investments.**
   From an energy systems perspective, it is common practice to evaluate the cost-effectiveness of energy saving investments with regard to the supply options available in economic terms, considering environmental or technical aspects through constraints imposed while performing energy systems optimisation. This method mostly assumes a socioeconomic perspective and disregards details about private, behavioural and socioeconomic aspects. As empirical studies suggest that such aspects matter in relation to the attractiveness of an investment, we consider ad-

ditional multidisciplinary methodologies tailored to the scope of the analysis. We thus report, test and assess outcomes from diverse methods including details about the impact of technical (e.g. various discount rates or energy price levels), socioeconomic and behavioural factors for adopting energy saving measures in different areas. The results highlight consistent modelling effects of using different types of methodologies while investigating on attractive energy savings investments, hence remarking the need of a broader and multidisciplinary approach when investigating on cost-efficient saving measures.

More specifically, we investigated on:

- **What are the characteristics of the most common models and methodologies to investigate on the optimal trade-offs between energy efficiency improvements and additional renewable energy supply, under different objectives?**
  Following the screening on a sample of studies investigating on the trade-off between energy efficiency improvements and additional renewable energy supply, we report considerations about tailored choices performed on international examples. The three main model types identified, bottom-up, hybrid and top-down energy systems models, can be related with the extent of the study, the specific aspects under investigation and the dimensional assessment of the analysis. Likewise, other characteristics such as stochasticity or multi-linear objective functions are linked to the scope of the study. Based on optimisation methodologies, with specific features tailored to every model considered, the studies point toward a path of integration between renewable-based technologies and energy efficiency measures, stressing the need of a trade-off. The analysis also identifies the need (and potential applications) for more detailed modelling methodologies optimising simultaneously the trade-offs, while aiming at future energy systems configurations where expedients for a wise use of energy are balanced.

- **How can we assess optimal investments in households electricity saving, from a consumer and energy systems perspective, and which impact do they have on the energy systems? Which socioeconomic and behavioural factors can influence the choice of investments in energy efficient household appliances?**
  To evaluate the most cost-effective savings solutions, we extend the formulation of Balmorel to include endogenous investments in energy efficient household appliances, including hourly profiles of energy consumption and electricity savings for each measure. To include aspects about private consumer perspective and assess the impact of the consumer choices on the energy systems, we develop a method

relating the cost-effective system and consumer investment decisions by soft-linking the energy systems model with a consumer investment model designed for the study. The outcomes show different levels and diversified choice of investments among the system and private perspective. The analysis also reveals the impact of energy investment behaviour at energy system level, not only on the Danish power system but also on the surrounding countries.

Investment measures can be attractive not only from a pure cost perspective, but also in relation to socioeconomic and behavioural factors, which can characterise investment probabilities in energy efficient appliance. Hence, on the bases of empirical survey data, we investigate on influential factors behind Danish consumer choice on the purchase of household appliances. Statistical results show that income, housing type, quantity of inhabitants, age, and end-use behaviour are predictors for choosing energy efficient appliances, with EE-index and housing type being the strongest of these predictors while income is weaker. Furthermore, the analysis highlights that specific daily energy-conservation actions are positively correlated with investment in efficient household appliances.

- **How to assess the cost-effectiveness of building-tailored heat energy conservation measures, for a residential building stock in a district heating area, from an end-user perspective, under different conditions? Is there an effect on exposing the private consumer to different heat tariffs, in relation to a potential uptake of energy savings measures?**
  On the bases of a case study on a sample building stock, considering gross and net saving potentials, we evaluate the cost-effectiveness of energy conservation measures based on net present value of cash flows comparing investments with the cost of heat consumption. In other scenarios, we study the effect of changes to the present district heating tariff structure, in order to make heat-cost components (i.e., consumption, capacity and subscription payments) variable. The investigation highlight variations in the level of investments according to building characteristics and measures types, with low energy performing buildings showing larger investments and measures such as windows and mechanical ventilation systems being the least attractive options. In regard to changes in the heat-tariff structure, when all cost components are made variable there is a considerable increase in the total cost-effective measures: in high energy performing buildings, investments are mostly linked to the subscription payment; for low energy performing buildings, most of the investments are related to the consumption and capacity components.

- **Which aspects characterise the structure of the industry and how can we adequately model a sector characterised by various end-uses and integrate it in established bottom-up energy systems models? Which ben-**

efits does the modelling gain by considering detailed temporal profiles of energy consumption?
On the basis of a screening performed on a Danish case, we highlight central characteristics of the industry, focusing on the structure of industrial energy use in regards to end-use processes, absolute and temporal aspects of energy consumption, and measures for fossil fuel reduction. We integrate altogether the considerations with a mathematical formulation that mirrors operational and technical aspects of industrial end-use processes, in regard to process heat demand and supply and we then implement such method in Balmorel. Although we do not quantify the impact of industrial changes in regard to e.g., energy savings, we develop the foundation for analyses that can simultaneously optimise dispatch and investments of the heat-and-power and industrial sectors, according to more stringent policies capping CO_2 emission levels and specific support schemes. To this end, the work performed on developing temporal profiles of process heat consumption for sectoral categories, enhance the quality of the analyses as it allows to investigate and discuss the co-integration of transformations regarding energy systems (e.g. additional renewables) and industry (e.g. electrification) on an hourly scale.

Overall, the results and insights from this thesis can be relevant for a number of different actors including:

- Energy systems modellers: the thesis develops methods to integrate optimal investments in energy conservation measures in the framework of energy systems optimisation models and methods to assess cost-effective investments from a private perspective, including considerations about socioeconomic and behavioural aspects;

- Policy makers: our results suggest energy policies to increase consumer awareness towards energy efficiency and savings, for instance, or analyse the impact of changes in the heat-tariff structure to foster the uptake of cost-effective heat savings measures in the residential building sector;

- Private consumers: our results emphasise how the end-user can benefit from investments in energy savings measures, for instance in economic terms by investing in household appliances.

In light of these considerations, the thesis concludes that there are un-exploited energy saving potentials which could be realised in a cost efficient way. The interdisciplinary methodologies employed, weighted with the benefits and drawbacks reported, have revealed to be efficient tools to investigate on the matter. As such, we mixed standard optimisation methods with consumer preferences and behavioural components, focusing on different sectors, thus providing a broader and more complete overview of the most efficient combination of savings and technologies.

The findings from the case studies, evaluated from a bottom-up engineering-economic perspective, provide directions for realisable potentials in the household and industry sectors and pose the bases for the design of incentives and policy instruments aiming at promoting least cost saving investment, targeting both measures and consumers behaviours. Being mostly related with Danish case studies, the outcomes cannot be generalised for other contexts, unless similar conditions apply. On the other hand the methods, integrating energy savings investments in energy systems models with details about temporal profiles of consumption and consumer behavioural aspects, can be relevant for broader international analyses. Considering the improvements on the energy systems model Balmorel, linking findings from sectorial energy savings potentials with energy systems aspects, investments in energy conservation measures and renewable-based energy technologies can be combined more cost-efficiently. In this way, the value of savings can be co-optimised in a model reflecting interconnected energy systems, paving the way for investigations on effective climate ambitious actions for Denmark and on the role of energy savings in a future with more renewable energy sources.

5.2 Future work

The work performed has touched upon most of the relevant objectives of the SAVE-E project, providing suggestions and specifics about cost-effective energy savings interventions, useful for policy markers, energy systems modellers and private end-users. Yet, there are aspects that could be worth to investigate further.

From a broader perspective, the present study could be extended in several key directions. One venue would be to study alternative scenarios with the combined modelling for all saving areas. Although individual approaches can be more suitable when exploring sectoral specifics, a broader approach, combining different aspects related with the problem, can lead to more exhaustive outcomes. In such optimisation framework, analyses can be performed not only as cost minimisation but also as a mean to investigate results under different objectives, being this the application of a new policy instrument or the study of a fossil-fuel free future.

Another venue could be to soft-link the results from Balmorel with top-down or hybrid energy systems models, to account for the limitations related with the partial equilibrium analysis, where changes in the energy systems are calculated assuming that all other actions (external to the energy sector) are frozen. As in reality changes in energy supply or demand are linked with other key sectors of the economy, it would be relevant to assume an integrated energy-economy approach, to evaluate the impact of changes at system wide scale including broader economic considerations. In this way, many of the limitations related to the methodologies employed for the thesis (See Section 3.4), such as behavioural realism, market distortion or intangible costs related to consumer choices, would be accounted for.

Regarding the chapters of this thesis, some of the models and methods could be extended to handle additional features and/or could be applicable to different contexts. Part of the limitations have already been highlighted in Section 3.4. Hence, below we indicate some directions for further research in connection with our papers.

- Chapters 7-8. In Chapter 7 we integrate an energy systems model with a simple consumer model while in Chapter 8 we develop a more sophisticated consumer behaviour model. An obvious extension of these papers would be to combine the energy systems model with the more advanced consumer model, and examine the effect on system and consumer investment choices.
- Chapter 9. In Chapter 9 we perform a thorough analysis of cost-effective energy conservation measures, tailored with characteristics from a building sample in a district heat network. The study could be extended to all the areas in Denmark, eventually including gross and net attractive investments in Balmorel and perform energy systems analysis. Such analysis should also include buildings with an individual heat unit, to compare the attractiveness of heat-saving options among different heat supply sources. Ultimately, the study could benefit from in-depth considerations about changes in the heat-tariff structure, assessing impacts and implications from a consumer, district heating company and energy systems perspective.
- Chapter 10. In Chapter 10 we develop a conceptual model of the industry sector in the framework of an energy systems model, posing the bases for combined analysis, without performing specific investigations. In this regard, future studies based on this work will benefit from a calibration of the model and an assessment of quantitative and qualitative changes at system scale, as a result of interventions (such as electrification or energy savings) in the industry sector.

Part II

Research work

Chapter 6

Optimal trade-offs between Energy Efficiency improvements and additional Renewable Energy supply: A review of international experiences

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Publication Status: Conference proceeding in *IEEExplore*

Abstract: Energy is a commodity used worldwide, representing a vital input for social and economic development. Due to continuous growth, energy demand has increased. Solutions have been proposed in order to satisfy the increase in demand, often implying the increase of capacity of the power mix. Meanwhile, current issues concerning climate change and fossil fuels depletion has moved attention towards cleaner ways to produce energy. This trend facilitated the breakthrough of renewable technologies. Since then, support policies have promoted the large deployment of renewables, without considering enough the improvements made in the energy saving field. Indeed, little attention has been paid to implement energy efficiency measures, which has resulted in scenarios where expedients for a wise use of energy (e.g. energy savings and renewables share) are unbalanced. The aim of this paper is to review and evaluate international experiences on finding the optimal trade-off between efficiency improvements and additional renewable energy supply. A critical review of each technique, focusing on purposes, methodology and outcomes, is provided along with a review of tools adopted for the analyses. The models are categorized and presented according to their main characteristics (e.g. bottom-up/top-down model, regional/national analysis, partial/general equilibrium, static/dynamic model). The results of this paper provide, to the decision-makers, informations useful to identify a suitable analysis for investigate on the optimal trade-off between renewables and energy efficiency measures in energy-systems under different objectives.

Keywords: Literature review · Energy systems models · Trade-off renewables and energy savings

6.1 Introduction

The enlargement of the energy sector in the past years brought a new problem since the green-house gases (GHG) emission related with energy production began to affect the environment, leading to global complications (IPCC, 2014). Various measurements and policies have been developed since then and, in vision of an international recognised effort, the Annex I countries signed the Kyoto Protocol in 1997 (Unfccc, 1998).

The recurrent issues concerning climate change and fossil fuels depletion has thus moved attention towards cleaner ways to produce energy. Among all, two valid solutions for reducing CO_2 emissions have been identified as the most relevant: energy efficiency improvements (EE) and generation by renewable energy sources (RES) (Ekins, 2004). The European Commission already acknowledge the positive contribution of EE and RES policies in the fight against GHG emissions identifying the measures as "no regret options for transforming the energy system (European Commission, 2012)" when analysing future scenarios for the year 2030 (De Alegria Mancisidor et al., 2009).

In vision of a greener future, different studies have analysed (with diverse goals and perspectives) the potential of implementing RES and EE in the energy systems (Del Rio, 2010; Rajakovi, 2015; López-Peña et al., 2012). Results often show that the implemented support policies have promoted large deployment of renewables, without considering enough improvements made in the energy saving field. Indeed, less attention has been paid to implement energy efficiency measures in energy systems modelling, which has resulted in scenarios where expedients for a wise use of energy (e.g. energy savings and RES' share) are unbalanced and cost-savings opportunities are missed (López-Peña et al., 2012; Taseska-Gjorgievska et al., 2013; Mallah and Bansal, 2010).

The causes of this non-perfect scenarios are to be found in the interactions and integration among these measures. Even though synergies among RES and energy efficiency are commonly acknowledged (Hennicke et al., 2004; Harmsen et al., 2011; IRENA, 2015; Lenard, 2009), the trade-off among them is still an un-explored field. Many studies have been investigating on future energy systems based 100% on renewable sources (Lund and Mathiesen, 2009; Krajacic et al., 2011; Connolly et al., 2011), as well as scenarios where energy efficiency measures contributes to GHG reduction and reduce energy demand (Brennan, 2010; Gillingham et al., 2003; Tao and Yu, 2011). However, just few studies have been focusing on the simultaneous implementation of policies regarding EE and RES in energy systems models and analyse their trade-off.

The aim of this paper is to review and evaluate the international experiences on the integration of energy efficiency measures and additional RES supply in the energy system. The screened studies have been analysed focusing on the different techniques, purposes, methodology and outcomes. Moreover, the tools used for the analyses have been categorised and presented according to their main characteristics. The article aims at being useful as: starting point for those not familiar with the topic, benchmark for authors who already deals with it, and as a guidance for decision makers in the process of identifying a suitable analysis to investigate on the optimal trade-offs under different objectives.

The article is structured as follows: Section 6.2 refers to the classification of the models and the studies selected. In Section 6.3 the categories previously introduced are used as a starting point to discuss the classification provided. Section 6.4 summarise on the findings, concludes on the topic and suggests future development on the matter.

6.2 Classification of the studies according to the categories

Before starting the analysis, a clarification is reported on the difference between synergy and trade-off, energy efficiency and energy savings since the terms are often misconceived. There can be *synergy* between two factors when their combined effect is greater (or smaller) than the sum of their separate effects (Luukkanen et al., 2006); on the other hand the *trade-off* refers to a method of reducing or forgoing one or more desirable outcomes in exchange for increasing or obtaining other desirable outcomes in order to maximise the total return or effectiveness under given circumstances (BusinessDictionary.com, 2014). Furthermore *energy efficiency* refers to the technical ratio between the quantity of primary or final energy consumed and the maximum quantity of energy service obtainable (heating, lighting, cooling,...), while *energy savings* implies the reduction of final energy consumption, through energy efficiency improvements or behavioural change (Oikonomou et al., 2009). For the trade-off investigation, both energy savings and energy efficiency concepts were considered.

6.2.1 Models

The tools adopted in the different analyses cover a wide range of characteristics. Those considered most relevant were used to categorise the models. The focus of the analysis will thus be on the analytic and mathematical approach selected when formulating the problem and writing the equations, on the type of resulting equilibrium and on the interfacing with the model's run-time (i.e. dynamicity). The results are reported in Table 6.1 where the models are listed in order of appearance in the studies presented in Tables 6.2-6.5 (i.e. ENPEP-BALANCE is used in (Christov et al., 1997), MASTER.SO in (López-Peña et al., 2012), and so on...).

Table 6.1: Analysis of the tools

Tool	Analytical approach	Mathematical approach	Equilibrium	Model
ENPEP - BALANCE[1]	Top-down	Non linear	Yes	-
MASTER.SO[2]	Bottom-up	Linear	Partial	Static
IOCM[3]	Bottom-up	Linear	Yes	Static
EnergyPLAN - GenOpt[4]	Bottom-up	Linear	Partial	Static
Remap 2030[5]	Spreadsheet based	-	Yes	-
PRIME 2007[6]	Top-down	Non linear	Partial	Static
MESSAGE[7]	Hybrid	Linear	Partial	Dynamic
MARKAL - TIME[8]	Bottom-up	Linear	Yes	Dynamic
MARKAL[9]	Bottom-up	Linear	Yes	Dynamic
MDDH[10]	Bottom-up	Linear	Yes	Dynamic
TIMES[11]	Bottom-up	Linear	Partial	Static
IRP[12]	Bottom-up	Linear	Partial	Static
IRSP[13]	Bottom-up	Non linear	Partial	Static
IRSP[14]	Bottom-up	Non linear	Partial	Static

Plenty of other models' features could be investigated and discussed. However, the aim of this section is not to report a full and complete description of the models along with their features, but rather to highlight the most relevant for the paper. For a thorough description of the models investigated, readers can refer to reviews about energy system models (Connolly et al., 2010; Urban et al., 2007; Pandey, 2002; Beeck, 1999).

6.2.2 Breaking down the studies

Despite the fact that some authors used the same model to perform the studies (e.g. MARKAL for studies (Taseska-Gjorgievska et al., 2013; Mallah and Bansal, 2010)), the reasons for the investigations were different. Therefore, the studies were analysed according to selected criteria: purpose of the study, methodology, results evaluation and conclusions of the studies. The results are reported in Tables 6.2-6.5. The intention of the categorisation is to:

- investigate on the reasons of the studies
- understand the methodology towards the final goal
- highlight the different ways to evaluate the results
- discuss and reflects on the final findings.

The findings are used for the discussion that follows, where results are then examined identifying common characteristics. In the Tables, DSM identifies Demand Side Management measures.

[1] (Conzelmann, 2001)
[2] (Lopez-Pena et al., 2013)
[3] (Dai et al., 2012)
[4] (Aalborg University, 2018)
[5] (Irena, 2014)
[6] (National Technical University of Athens, 2016)
[7] (International Institute for Applied Systems Analysis, 2016)
[8] (Loulou et al., 2004)
[9] (Loulou et al., 2004)
[10] (Dias et al., 2010)
[11] (ETSAP, 2018)
[12] (Nguyen and Ha-duong, 2009)
[13] (Hu et al., 2010)
[14] (Yuan et al., 2014)

Table 6.2: Analysis of the studies reviewed

Model	Purpose of the study	Methodology	Assessment of the results	Conclusions of the study
ENPEP-BALANCE[15]	Analysis of GHG mitigation options	Simulation-based optimisation: cost-efficient energy scenario to mitigate GHG emissions	USD/tCO_2, T CO_2 emitted	• CO_2 mitigation measures investigated leads to reduction in energy demand and CO_2 emission
MASTER .SO[16]	Comparison on the costs of achieving CO_2 reduction level through RES or EE support (ex-post analysis)	Maximise energy system sustainability (i.e. least cost-environmental energy supply options) while satisfying model's constraints	System costs (for each sector), economic savings for each scenario, CO_2 emissions, capacity installed	• DSM dominates RES support if the emission reduction at minimum cost is the only concern • DSM measures facilitate the investments in RES • RES are anyway required in vision of a fully decarbonised energy sector
IOCM[17]	Describe, investigate and prove CO_2 mitigation measures within Chinese energy power system on the demand and supply side	Multi-objective optimisation: cost-effective optimal plan of energy supply and demand side investments	Capacity installed, CO_2 mitigation of virtual energy	• DSM and smart grid operation leads to environmental enhancements • EE and RES planned measures will not be enough to reach the final target
Energy PLAN-GenOpt[18]	Planning of sustainable national energy system under EU2030 policy framework (27% primary energy reduction, 27% RES in final energy consumption, 40% CO_2 emission reduction)	Simulation-based optimisation: minimise the cost of the system for optimal energy policy mix implementation under constraints	% decrease in primary energy, % increase in RES share, % decrease in CO_2 emissions	• Optimal combination of economically justified RES and EE measures • Low market price imply no participation of the RES w/o subsidies • EE economic potential exist even without the EU2030 targets

Table 6.3: Analysis of the studies reviewed

Model	Purpose of the study	Methodology	Assessment of the results	Conclusions of the study
Remap2030[19]	Doubling the rate of improvements in EE and the share of RES in the selected countries' energy mix	Identification of measures to fulfil SE4all and RES objectives, study of synergies and trade-off from deploying EE and RES simultaneously	CO_2 emissions avoided, RES share in power generation and TFEC, energy savings in TFEC and TPES	• RES strategies reduce primary energy • EE polices lower energy demand and increase share of RES • Synergies reduce demand growth up to 25% • Trade-off needed to avoid hinder of RES deployment by EE policies
PRIME2007[20]	Compute and demonstrate RES contribution to the Europe's 2020 EE targets	Assessment of the contribution of RES through the Primary Energy Method. Scenarios comparison analysis.	Primary energy savings, cost of DSM measures	• RES clearly contributes to the EE targets • DSM measures can hinder the development of RES (binding targets problem)
MESSAGE[21]	Synergies between climate change mitigation and energy related objectives for sustainable development.	Formulation and evaluation of alternative energy supply strategies according with constraints implemented	Energy related investments, policy costs, CO_2 price, GHG concentration	• RES energy supply and end-use EE useful to achieve low stabilisation target • stronger focus on EE leads to lower system costs, exclusion of supply side plants from mitigation portfolio
MARKAL-TIME[22]	Analysis of the influence of EE and RES programs and policies in the development of the energy system (energy security, diversification, economic competitiveness, CO_2 mitigation)	Simulation-based optimisation: minimisation of the system costs, adequately discounted over planning horizon, while satisfying constraints.	Energy system costs, primary energy supply, new power capacity, final energy consumption, CO_2 emissions	• EE case shows the greatest CO_2 reduction with the lowest system costs • EE and RES case shows better results for CO_2 emission reduction, however with higher system cost

Table 6.4: Analysis of the studies reviewed

Model	Purpose of the study	Methodology	Assessment of the results	Conclusions of the study
MARKAL[23]	Determination of policies guidelines and interventions in the Indian power sector to follow a sustainable development path.	Determination of the least-cost pattern of technology investments and utilisation (comparative analysis) to calculate the resulting pollutants	CO_2 emissions, RES and efficiency power plants (EEP) installed capacity	• Least cost-effective actions on CO_2 emissions and demand reduction lies on EE measures • RES will cover up to 25% of the system and will contribute to the CO_2 emission reduction • EE and RES combined leads to the best achievements in terms of CO_2 emission reduction
MDDH[24]	Calculate the cost of investments and CO_2 emissions in electricity generation facilities that can be avoided implementing EE policies/measurements	Comparative analyses scenarios: cost/emissions savings evaluation in an energy systems highly based on uncertainties	Energy and CO_2 emissions savings	• EE investments are preferable to RES investments • Increase of EE policies reduce energy system's operating costs • Additional EE measures implementation still cheaper than new RES project (already selected)
TIMES[25]	Analysis of the impact of DSM options (e.g EE measures, dynamic demand response) in a closed system characterised by high RES penetration	Minimisation of investments and operation costs of RES sources with different DSM options acting on energy demand	RES capacity installed, energy production by source, automation of domestic machines	• DSM strategies delay the investments in RES in the system and improve the operation of already existing plants
IRP[26]	Analysis on the DSM options' (EE improvements) implications for capacity expansion planning in power sector (with rebound effect)	System-cost minimisation, both for demand and supply side, while adhering to constraints.	Avoided capacity, avoided emissions (CO_2, NO_x, SO_2)	• Cost-effective selected DSM measures reduce the CO_2 emissions • Rebound effects considered will reduce the savings

Table 6.5: Analysis of the studies reviewed

Model	Purpose of the study	Methodology	Assessment of the results	Conclusions of the study
IRSP[27]	Assessment of IRSP performances against IRP models on the integration of EE measures in the Chinese power sector (maximum economic/social benefit return, minimum resource input	Cost-effectiveness choice maximisation optimising the equilibrium between conventional/RES plants and efficiency power plants	Capacity installed and avoided, emissions' savings, total system costs	• IRSP model performs better then IRP due to the better integration of efficiency and conventional power plant
IRSP[28]	Comparison among power planning pathways under different policies for the promotion of EEP and RES	Costs minimisation through optimisation, demand and supply side (external, internal and popularisation costs)	Capacity installed, pathway of resource allocation	• Decrease in efficiency power plants, with popularisation costs • Non linear IRSP pathways provide a better representation of the supply curve

[15] (Christov et al., 1997)
[16] (López-Peña et al., 2012)
[17] (Dai et al., 2012)
[18] (Rajakovi, 2015)
[19] (IRENA, 2015)
[20] (Harmsen et al., 2011)
[21] (Van Vliet et al., 2012)
[22] (Taseska-Gjorgievska et al., 2013)
[23] (Mallah and Bansal, 2010)
[24] (Calili et al., 2014)
[25] (Pina et al., 2012)
[26] (Shrestha and Marpaung, 2006)
[27] (Hu et al., 2010)
[28] (Yuan et al., 2014)

6.3 Outcomes: comparison and assessment

6.3.1 Models

Following the categorisation reported in Table 6.1 the results are here commented. A common factor that joins together all models is the optimisation methodology, certainly related to the nature of the final goals of each analysis. Only one model (MDDH) deals with stochasticity. The reasons being that the model deals with an electrical power system with strong hydro generation, thus requiring stochastic techniques to deal with the uncertainties in the water-stream flows (Souza et al., 2012; Dias et al., 2010).

Most of the models are bottom-up, one is hybrid (i.e. combines both top-down and bottom-up approach) and two are top-down. Usually, models referred as top-down emphasise economy-wide features, while bottom-up focus more on sectorial and technological details. The choice of bottom-up models is thus in line with the goal of most of the research questions: investigating possible configurations of future energy systems.

Depending on the degree of complexity of the analysis on the objective to optimise, the models were classified as linear and non linear. While the theoretical difference among the two methods is commonly acknowledged, it was found that those models which presented non linearity were either considering a multi-objective optimisation approach (Yuan et al., 2014; Hu et al., 2010), considering non-linear cost supply curves of resources used in power generation (Harmsen et al., 2011) or including non linear modules while solving the optimisation (Christov et al., 1997)(e.g. BALANCE module for ENPEP (Conzelmann, 2001)). The models are also classified according to the feature of static or dynamic modelling, where the main difference lies in the fact that a dynamic model is, in general, a model describing the state evolution of a system over time while a static model has a time independent view of a system (Apolloni et al., 2005). Among all the models considered, only MARKAL, MESSAGE and MDDH considered a dynamic mathematical approach; all the other, for a matter or simplicity, considered a static approach.

Concerning the final equilibrium in the markets, the tools can be categorised according to the level of inspection. When the aim is to investigate the changes in a particular sector without considering the interaction of this last with the whole system, then the model will be classified as partial equilibrium. On the other hand, a model will be labelled as general equilibrium if the assumption is that every market has an effect on every other market and therefore a change in one market may result in changes in another market. A close observation of the results reported in Table 6.1 shows that there is a fair split between the two categories, thus implying that half of the studies has been focusing entirely on a sector (i.e. energy sector), while the others investigated the goals considering the changes in different sectors and the interactions among them.

6.3.2 Studies

The studies selected were investigated according to the selected criteria previously introduced. The resulting considerations from the results in Tables 6.2-6.5 are here remarked. The purposes can be divided in three categories: (1) GHG/CO_2 mitigation options investigation, (2) targets fulfilment study and (3) analysis of policies and programs development. According to this division, highlighted in the tables with double separation lines, the studies (Christov et al., 1997; López-Peña et al., 2012; Dai et al., 2012) belongs to the first category, (Rajakovi, 2015; IRENA, 2015; Harmsen et al., 2011) to the second, while the remaining to the third (see Tables 6.2-6.5).

Concerning the technique adopted, due to the nature of the models and the way the problems were mathematically formulated, almost all the studies follow the "system operation/investments-cost minimisation while adhering to constraints" approach. Besides, the policies objectives are implemented as constraints on the different variables under investigation.

The results of the analysis are assessed with different indicators, usually related with the focus of the analysis. Among the most employed there are: decrease in primary energy (due to energy savings), increase in RES share, CO_2 emission levels, new capacity investments as well as policy cost, cost of emission reduction, energy system costs, economic savings and CO_2 emissions avoided.

Regarding the conclusions of the studies, the findings point to similar outcomes. Among the most supported, there are the following:

- EE measures are the most cost-effective options for CO_2 reduction in energy systems
- EE measures should be implemented first, RES after
- RES energy supply and end-use EE is the best combination to achieve low system energy costs and high CO_2 reduction (however, with higher system prices)
- Synergies between RES and EE are commonly acknowledged, while trade-offs are still well not defined
- Attention must be paid to the rebound effect since it can decrease the savings (economic, energy and emissions)

- EE measures imply popularisation costs (necessary to spread the knowledge) that can hinder their development.

In support, an analysis performed on the Spanish sector (López-Peña et al., 2012), reported that if the reduction of emissions at a minimum cost is the only concern, implementing EE measures would led to almost 5 €mil of savings (both in RES promotion and to meet the reduced demand).

Moreover, on the interaction between EE-RES, the EE measures can act both positively and negatively. In the short term, the increase of EE measures leads to a decrease of the energy demand, thus increasing the share of RES in the system and fostering their use (Marques and Fuinhas, 2011). In the long term, the additional measures towards efficiency hinder and delay RES deployment, since the reduced energy demand is already covered by a well balanced energy system (Harmsen et al., 2011; Pina et al., 2012).

Different studies have already acknowledge the significance of the rebound effect and popularisation costs when analysing EE implementation in energy systems (Sorrell et al., 2009; Madlener and Alcott, 2009; Greening et al., 2000). The magnitude is usually estimated in a range between 0% and 30% (rebound) (Madlener and Hauertmann, 2011) and 20% (popularisation) (Yuan et al., 2014) of the savings gained, thus making both of them essential factors to consider in analyses of energy system highly based on EE.

Nevertheless, a proper mix of measures on both demand and supply is necessary in order to gain significant emission reduction (Cosic et al., 2011). Hence both EE and RES are necessary. The challenge then is to coordinate support policies in order to achieve the desired result at the lowest cost.

6.4 Conclusions

When planning future development of the energy system it is important to focus on the trade-off between energy efficiency improvements and additional renewable energy supply. The reasons lies on economical and environmental benefits that can be gained by such investigation. The trade-off can be found to be different from system to system depending on the structure of the already existing energy system, on the availability of RES sources/EE measures and on the potential of implementation of such. Thus contextualisation is an important factor when comparing different trade-offs outcomes.

The goal of the paper was to analyse studies that investigated on the trade-off between RES and EE. The selected studies along with the models used were split in categories.

The features of the tools were found to be different according to the kind of investigation performed. Concerning the studies, the analysis highlighted that the purposes could be gathered in three categories (GHG/CO_2 mitigation options investigation, targets fulfilment study and analysis of policies development). Moreover, all the studies point toward a path of integration between RES and EE measures. A trade-off is nonetheless necessary in order not to hinder the development of the RES.

Finally, just few studies were found to be focusing entirely on finding the optimal trade-off, highlighting the lack of examples in the literature about the topic. Questions like "What should be the share of RES and EE in the system, given a pre-defined goal" and "Which technologies/measures are more suitable to cover the share for each system" should be answered by these kind of studies. Future works of future modellers should thus strength the focus on finding the trade-off (RES-EE) for each of the investigated systems. The results of these analysis will lead to shape future energy systems towards configurations where expedients for a wise use of energy will be balanced.

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Chapter 7

Modelling of electricity savings in the Danish households sector: from the energy system to the end-user

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Abstract: In this paper we examine the value of investing in energy-efficient household appliances from both an energy system and end-user perspective. We consider a set of appliance categories constituting the majority of the electricity consumption in the private household sector, and focus on the stock of products which need to be replaced. First, we look at the energy system and investigate whether investing in improved energy efficiency can compete with the cost of electricity supply from existing or new power plants. To assess the analysis, Balmorel, a linear optimization model for the heat and power sectors, has been extended in order to endogenously determine the best possible investments in more efficient home appliances. Second, we propose a method to relate the optimal energy system solution to the end-user choices by incorporating consumer behavior and electricity price addition due to taxes. The model is non-exclusively tested on the Danish energy system under different scenarios. Computational experiments show that several energy efficiency measures in the household sector should be regarded as valuable investments (e.g. an efficient lighting system) while others would require some form of support to become profitable. The analysis quantifies energy and economic savings from the consumer side and reveals the impacts on the Danish power system and surrounding countries. Compared to a business-as-usual energy scenario, the end-user attains net economic savings in the range of 30-40 EUR per year, and the system can benefit of an annual electricity demand reduction of 140-150 GWh. The paper enriches the existing literature about energy efficiency modeling in households, contributing with novel models, methods, and findings related to the Danish case.

Keywords: Energy efficiency · Household appliances · Consumer investments · Energy system modeling · Emissions reduction

7.1 Introduction

In compliance with the recent international effort towards the climate change mitigation (European Commission, 2010), Denmark has set its goals for the year 2020 and is working to fulfil the targets concerning renewable energy (RE) integration in the system and energy efficiency (EE) improvements. Compared to the 1990 levels, Denmark has reduced its greenhouse gas emissions by more than 30% and, according to the current policies and trends, the Danish Energy Agency forecasts that the reduction will reach almost 40% by 2020 (Breum, 2015), thus exceeding the legally binding EU commitment of 34%. Denmark can vaunt one of the highest contributions of renewables in any energy system worldwide (excluding hydro-power), with a 56% contribution in 2014. In particular, in 2015, more than 40% of the Danish electricity demand was satisfied by wind energy, and this figure is expected to increase up to 50% by 2020 (Breum, 2015). Besides the effort in integrating renewables in the energy system, the Danish government has set a number of targets for the further development of EE measures. According to the National 2020 Energy Efficiency Targets, Denmark is aiming to reduce the primary and final energy consumption by 12.6% and 7.2% respectively compared to 2006 (Danish Energy Agency, 2014).

Both RE and EE measures have been identified by the European Commission as the most suitable options to evolve the national energy systems towards greener configurations

(European Commission, 2012). Nevertheless, if not properly enforced, the simultaneous implementation of RE and EE can lead to sub-optimal investment planning and missed cost-saving opportunities (Baldini and Klinge Jacobsen, 2016). The challenge is to identify the optimal trade-off between EE levels and power system configurations while exploring future scenarios, i.e. understanding where to invest in order to obtain the most cost-effective energy system given a target on emission reduction. Several studies, for instance, have shown that enhancing EE is likely the most cost-effective way to reduce carbon emissions in the medium term (López-Peña et al., 2012; Enkvist et al., 2007).

The literature has then considered the modelling of EE in households along two main lines: the heat and electricity sector. Available literature presents many examples from the Danish heating context, while EE literature from the electricity sector is lacking, whereby we broaden our perspective.

On the heat sector side, Zvingilaite (2013) models heat savings in the Danish building sector using a heat and power optimisation model, showing that the attainable level of heat savings can reach up to 11% of the projected heat demand in 2025. At the time of publication, the study represented the front-runner implementation of heat savings as endogenous investment variables in an energy system model, thus providing a first estimation of the cost-effective heat savings level from a socio-economic perspective. Several studies target environmental goals as CO_2 emission reduction, stressing the need to identify the trade-off between heat savings and heat supply. Connolly et al. (2014) examine the joint role of district heating and heat savings to decarbonise the EU energy system, and conclude that coupling the two measures can help reducing primary energy supply and CO_2 emissions at the lowest costs compared to other alternatives. Zvingilaite and Klinge Jacobsen (2015) investigate the trade-off between heat savings and heat generation technologies in the Danish energy system, focusing on the residential investment behaviour and including health costs. The study reveals that savings up to 24% of the heat demand can be achieved with an optimal configuration of investments in heat savings and heat generation technologies. Hansen et al. (2016) estimate the optimal heat savings investment levels within various European countries. This level is identified in investments aimed to reduce the projected heat demand of about 30-40%, while supplying the remaining demand with sustainable heat technologies.

On the electricity side, the literature suggests that disaggregating the household electricity demand into different appliances is the starting point for modelling EE measures and the attitude of consumers towards them (Lefebvre and Desbiens, 2002; Evora et al., 2011; Batih and Sorapipatana, 2016). Rodriguez Fernandez et al. (2015) propose the use of machine learning techniques to identify individual electrical devices in households based on power consumption, so that specific appliances can be targeted for efficiency improvement. Numerous authors then focused on the trade-off between electric energy savings in households and power supply with interesting examples, close to the direction of our work, in an Asian context. Parikh and Parikh (2016) examine the potential energy and emission savings from choosing energy-efficient home appliances in India. Based on the 5-star-rating EE promotion program, the authors modelled the attitude of consumers (poor and rich) in adopting more efficient appliances. The results show that, given the awareness of consumers concerning the various options of efficient appliances, a demand and emissions reduction from households exceeding 30% can be reached in 2030. Batih and Sorapipatana (2016) analyse the electricity consumption of urban households and its saving potential in Indonesia. Similar to the Indian's case, the results illustrate how implementing specific EE improvements can lead to a reduction of 21% of both power demand and CO_2 emissions from households by 2030. Xie et al. (2016) prove that energy management strategies in the Chinese household sector should include investments in energy-efficient home appliances. The policy recommendation is thus in terms of subsidies driving customers to purchase a higher share of energy-labelled appliances. Mizobuchi and Takeuchi (2016) examine the influence of an increase in purchasing energy-efficient home appliances on the power system in Japan. The conclusions are in line with previous studies, showing that households with new energy-efficient appliances can save a large amount of electricity, but also that the rebound effect may cancel part of the savings out due to a more intense use of the appliance. Finally, a few studies consider the contribution of appliances to the household electricity use with a global scope, illustrating the huge potential of energy efficiency improvements in the global residential sector (Wada et al., 2012; Cabeza et al., 2014).

As indicated by the consistent amount of literature, in the residential sector lies a large potential for EE improvements. In Denmark, electricity consumption from private households exceeds 20% of the total load (Klinge Jacobsen and Juul, 2015). This figure is also expected to increase in the next years due to the upcoming electrification of the household facilities, and should then be balanced with improvements in energy efficiency measures (Bartiaux and Gram-Hanssen, 2005). The electricity consumption in the household sector is mainly related to the different home appliances. Therefore, if electricity savings could be targeted to the different appliance categories, then lower consumption profiles associated to the households could lead to savings for the system in terms of necessary power plants, capacity investments and emissions. Furthermore, the electricity savings may have different effects on the power system depending on the hourly consumption profile of the appliance category whose demand is reduced.

Using a bottom-up approach (Swan and Ugursal, 2009), the analysis proposed in this paper will make use of hourly consumption profiles of home appliances determined in previous studies (Klinge Jacobsen and Juul, 2015) to investigate the effect of EE improvements in the Danish energy system. In particular, the aim of this paper is threefold:

1. to evaluate from a system perspective whether it is worth to invest in more energy-efficient appliances rather than install new power plants, and observe the effects on the energy mix;

2. to assess from an end-user perspective which energy-efficient appliance should be regarded as a profitable investment, taking into account the behavioural dimension of the consumer;

3. to compare the investment choices of the model according to the system and consumer perspectives.

The paper enriches the existing literature about EE modelling in households, contributing with new models, methods, and findings related to the Danish case.

7.2 Methodology

7.2.1 Overview of Balmorel

Balmorel is a linear programming-based optimisation model for the energy sector, originally developed in 2001 to analyse the Baltic system (Balmorel, 2018). The model finds economically efficient dispatches and optimal capacity investments for the energy system. The emphasis is on the electricity and combined heat and power (CHP) sectors, and the major technologies for electricity, heat generation and storage are included in the model.

The model consists of a set of neighbouring countries that participate in various electricity markets. Each country is then split into one or more regions, depending on the market features, where electricity can be traded with constraints. Denmark, for instance, is modelled using two electricity zones, Denmark East and Denmark West (in the following DK-E and DK-W), according to the NordPool system. The electricity transmission between adjacent zones is limited by a given transmission capacity. Moreover, to model the CHP sector, each electricity region is further divided into several district heating areas.

Time in Balmorel is organised into three step categories: years, seasons (weeks) and individual time units (hours). Each year is composed of 52 weeks and each season is, in turn, composed of 168 time units. The time is however flexible and the user can decide how many seasons and time units to use in the model. The choice depends on the needs for the specific investigation and typically ranges from weeks, when the focus is operational, to years, common for investments analyses. The running time of the model is influenced by the time aggregation used, and varies from minutes to several hours. The main output is, among others, electricity and heat production levels, electricity prices, system costs, electricity transmission and emissions.

Despite being used in the industry (Balmorel, 2018), Balmorel has been applied by the research community to several energy systems worldwide and for a wide range of purposes, from the integration of renewable technologies in the energy mix, to the analysis of market conditions, policies implementation, and future role of district heating in energy systems (Ball et al., 2007; Jensen and Meibom, 2008; Karlsson and Meibom, 2008; Münster et al., 2012; Münster and Meibom, 2010). Balmorel has also been used to integrate heat savings and residential investment behaviour into the energy systems (Zvingilaite, 2013; Zvingilaite and Balyk, 2014; Zvingilaite and Klinge Jacobsen, 2015).

7.2.2 Modelling investments in household appliances

Consider a set of home appliances $i \in \{1, \ldots, I\}$, and a set of electricity zones $r \in \{1, \ldots, R\}$ where we allow investments in energy-efficient appliances (in our study DK-E and DK-W). To extend Balmorel with EE investments, we need to introduce first the following group of parameters. The assumptions behind data and how data is collected will be topic of the next section.

- ξ_i^{max} = maximum consumption reduction for appliance i with respect to a baseline new, non-EE appliance of the same type and functionality [kWh/year]. For example, assume that the average consumption for new, non-EE refrigerators is 300 kWh/year, and the average consumption of the most efficient refrigerators, of same type and functionality, available in the market is 180 kWh/year, then the maximum annual electricity saving from a refrigerator is $\xi_i^{max} = 300 - 180 = 120$ kWh/year.

- c_i = additional cost of investing in a single appliance i with maximum saving of ξ_i^{max} [EUR] with respect to the cost of a baseline consumption class. For example, assume that the baseline refrigerator efficiency class is A with average cost of EUR 650, and the most efficient is A+++ with average cost of EUR 1000, then c_i = EUR 350.

- ρ = discount rate, used to annuitise the investment cost of new appliances. More comments on the discount rate will follow in the case study.

- L_i = average lifetime of appliance i [years]. The lifetime is used to annuitise the investment cost and to approximate the annual substitution rate of the appliances, by computing $1/L_i$.

- N_{ir} = estimated number of appliances i in region r. It can be approximated by multiplying the share of an appliance with the number of households; for example, if the share of washing machines is 0.80 [items/household] and the number of households in DK-W is 1.4 mln., then N_{ir} is $0.80 \cdot 1.4 = 1.12$ mln. Our construction of N_{ir} applies if the total stock of appliances is fixed over time, as it is for the Danish market where household growth is very low. For developing economies, such as China or India, N_{ir} should be time-dependent.

- $n_{ir} = N_{ir}/L_i$ = estimated number of appliances i in region r which are replaced on average every year (e.g. because they are too old and not well-functioning anymore). For instance, if the average lifetime of a dishwasher is $L_i = 10$ years and the existing stock in DK-E is $N_{ir} = 1$ mln., then approximately $n_{ir} = 0.1$ mln. dishwashers are expected to be purchased in DK-E during a year.

- d_{irt} = gross electricity consumption [MWh] in region r due to the appliance category i at hour t of the year. We also define the total annual consumption of appliance i in region r as $D_{ir} = \sum_t d_{irt}$, and we will refer to the collection $\{d_{irt}\}_t$ as the yearly *consumption profile* of appliance i in region r.

We summarise the set of parameters necessary to implement the model in Table 7.1.

Table 7.1: Data required to implement the model extension

Name	Description	For each
ξ_i^{max}	Max. consumption reduction	appliance
c_i	Extra cost of more efficient appliance	appliance
L_i	Lifetime of appliance	appliance
N_{ir}	Stock of existing home appliances	appliance and region
ρ	Discount rate	-
d_{irt}	Hourly consumption profile	appliance and region

It is now possible to compute the annuitised extra investment cost of a new EE appliance, c_i^a [EUR], as

$$c_i^a = \frac{\rho\, c_i}{1 - 1/\left(1+\rho\right)^{L_i}}.$$

Then, we define the decision variables $x_{ir} \in [0, 1]$ as the percentage of new appliances of type i that are replaced with the most energy-efficient version in region r. In particular, $x_{ir} = 0$ means that there is no investment in more efficient appliances of category i, while $x_{ir} = 1$ means that the full amount n_{ir} of appliances i in the region is upgraded. In this case, the system will benefit of an annual electricity saving of $\xi_i^{max} n_{ir}$ for the lifetime of the appliance.

The introduction of investments in EE has two main effects in the energy system model. First, the investment cost represents a new contribution in the objective function, given by

$$\min : SysCost + \sum_{i=1}^{I} \sum_{r=1}^{R} c_i^a \, n_{ir} \, x_{ir} \tag{7.1}$$

where $SysCost$ is the original objective function in Balmorel representing the total cost of the energy system, and includes the cost of fuel consumption, operation and maintenance cost for the different technologies, investment cost in new generation and storage capacity, emission and fuel taxes etc. Second, the demand profile is reduced according to the saving associated with x_{ir}. The saving is spread over the whole year and applies with the same percentage across the consumption profile of the appliance. We can consequently work hour by hour and, denoting with d_{rt} the electricity demand in region r and time t, we define a new power balance equation

$$\text{(electricity supply in } r \text{ at } t) = d_{rt} - \sum_{i=1}^{I} \frac{d_{irt} \, \xi_i^{max} \, n_{ir} \, x_{ir}}{D_{ir}}. \tag{7.2}$$

For instance, if there is no investment in EE, meaning $x_{ir} = 0$ for all appliances i, then the summation term (i.e. the saving) is zero and the equation reduces to the original one. If the investment is maximum for appliance i, i.e. $x_{ir} = 1$, then the demand is reduced by a factor $d_{irt} \, \xi_i^{max} n_{ir} / D_{ir}$. This amount corresponds to the annual saving $\xi_i^{max} n_{ir}$ from appliance i, scaled with the fraction of total demand D_{ir} occurring in hour t, d_{irt} / D_{ir}. In line with the other investments in Balmorel, in Eq.(7.2) it is implicitly assumed that new appliances are purchased and installed in the first hour of the year.

In addition, several studies suggest that the gains achieved from new energy saving measures are usually slightly lower than what initially expected, due to the so-called *rebound effect* (Khazzoom, 1980; Carnall et al., 2015; Bulu and Topalli, 2011; Shrestha and Marpaung, 2006; Galvin, 2010; Farinelli et al., 2005; Galarraga et al., 2013). This happens because the consumer typically responds to new EE measures in a way that tends to offset the effects of the changes. In more practical words, if we have a more efficient appliance or service, we tend to use it more because its use is cheaper, and we may also purchase additional appliances of the same type. We include the rebound effect in our model and characterise it as a linear response. Introducing $\beta_{ir} \in [0,1]$ and indicating with D_r the total yearly electricity demand in region r, we extend Eq.(7.2) with

$$\begin{aligned}(\text{electricity supply in } r \text{ at } t) = d_{rt} - \sum_{i=1}^{I} \frac{d_{irt}\, \xi_i^{max}\, n_{ir}\, x_{ir}}{D_{ir}} \\ + d_{rt}\, \frac{\sum_{i=1}^{I} D_{ir}}{D_r}\, \frac{\sum_{i=1}^{I} \xi_i^{max}\, \beta_{ir}\, x_{ir}}{\sum_{i=1}^{I} \xi_i^{max}}.\end{aligned} \tag{7.3}$$

Even though the magnitude of the effect might change depending on appliance and region, in the following we set all variables to be the same ($\beta_{ir} = \beta$).

To summarise, investing in efficient household appliances reduces the electricity consumption as in Eq.(7.3). Less demand implies that less production technologies to operate or install are needed to supply electricity, which in turn implies lower costs for the system. The optimisation process will then implicitly compare this economic saving with the investment cost added to Eq.(7.1) and, if convenient, will endogenously trigger the investment.

7.2.3 From the energy system to the end-user

The model presented optimises investments from a system perspective. It is a socio-economic analysis and does not include taxes on the consumer side. This means that the solution resulting from the optimisation process should be interpreted as the least expensive solution for the whole energy system, and investments in energy-efficient appliances implicitly compete with the supply of electricity at the system price, i.e. wholesale market price. However, the analysis currently disregards a representation of the end-user choices, which are relevant since in practice investments in home appliances are made by end-users. The consumer pays a higher price for electricity due to additional taxes on e.g. transmission, distribution, and policy costs for promotion of renewables. In Denmark, the tax addition to the electricity price is a fixed additive amount that makes the consumer's price up to ten times higher than the system price (Energitilsynet, 2016). As a consequence, investments which are not worth for society might be actually profitable for the single user, who individually evaluates an EE investment.

To include the consumer utility in the analysis, we propose the following sequential approach. First, the consumer observes the annual electricity price profile generated from the system model and estimates the consumer price by considering an average overpricing factor. Second, the consumer determines whether investing in more energy-efficient appliances is profitable by comparing the extra investment cost with the economic saving implied by the consumption reduction. Third, the energy system model is solved for the second time embedding the investment decisions of the consumer. New electricity prices are generated, and the actual saving on the consumer side is determined together with possible changes in the energy system. Figure 7.1 summarises the sequential process.

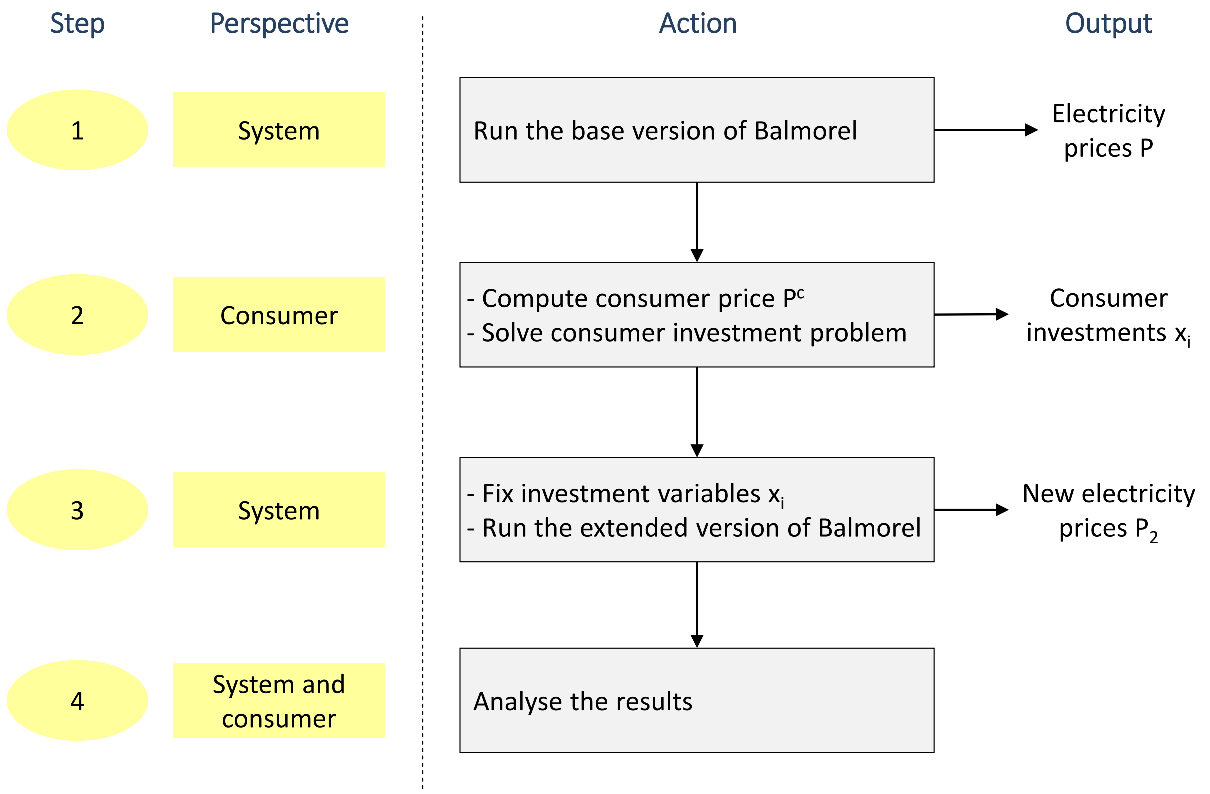

Figure 7.1: Sequential process to analyse investment decisions for end-users

Let us focus on the consumer model. When should a consumer purchase a new energy-efficient appliance, e.g. a refrigerator? If the refrigerator is well-functioning, one would generally need some strong incentive to replace it with a more efficient product. However, as discussed earlier, by introducing a substitution rate we limit the analysis to the sub-group already needing to replace the given appliance due to capital depreciation. Thus, the question we try to answer is more specific: I need to purchase a new refrigerator, should I invest in a very energy-efficient product, paying an extra cost but having an annual energy saving, or should I buy an average refrigerator similar to what I had before? A rational consumer would compare the extra investment cost of the more efficient product with the expected economic saving resulting from the consumption reduction throughout the appliance lifetime, and would undertake the EE investment in case of positive Net Present Value (NPV) of cash flows. In particular, we denote with p_{rt} the system price of electricity, which in Balmorel corresponds to the dual value of the power balance equation, and with γ

the average price overcharge on the consumer side. The consumer price is then estimated by $p^c_{rt} = p_{rt} + \gamma$ and the NPV of an EE investment is computed for every appliance i and region r with

$$NPV_{ir} = -c_i + \sum_{y=1}^{L_i} \frac{\alpha_y}{(1+\rho)^{y-1}} \left(\sum_{t=1}^{T} p^c_{rt}\, d_{irt}\, \xi_i^{max} / D_{ir} \right). \tag{7.4}$$

Eq.(7.4) represents the trade-off between extra investment cost and cumulative annual saving. The expression inside brackets is the economic saving for the current year, calculated by multiplying the consumer price at a given hour t with the consumption reduction achieved in t, then summing over the whole year ($T = 8760$ is the number of hours in a year). This expression is then summed over a number of years corresponding to the lifetime of the appliance L_i, discounted, and multiplied by a factor α_y indicating the expected change (increase or decrease) of electricity prices for year y.

In practice, however, a consumer does not act in a fully economically rational way and there are behavioural aspects that may influence the investment decision. The consumer behaviour is difficult to capture and model since it is by definition subjective. Previous research tried to quantify the correlation between the propensity to invest in EE (intended as both housing renovation and the purchase of energy-efficient appliances) and factors like income, age and education (Hausman, 1979; Mills and Schleich, 2010; Ward et al., 2011; Murray and Mills, 2011; Allcott, 2011b; Davis and E. Metcalf, 2014; Houde, 2014; Newell and Siikamäki, 2013; Schaffrin and Reibling, 2015; Bartiaux and Gram-Hanssen, 2005). Most of the studies agree on a positive correlation between household's income and investments level. In contrast, conclusions regarding other factors (age, education etc.) often show ambiguity and there is generally no statistical significance in the correlation with investments.

In line with these studies, we include in the model a *behavioural uncertainty* related to the household's income level. A low income household might not be willing to pay a high up-front cost for relatively small annual electricity savings. Consequently, even though the EE investment turns out to be profitable according to Eq.(7.4), it may not be undertaken because the payback period is too long. The choice also depends on the other expenses of the households in the same period, i.e. your overall liquidity constraints. On the other hand, the up-front investment cost for a high-income household is typically not a constraint, and, if the EE investment is profitable, then it will be undertaken. It can be seen as a sort of budget constraint and a linear probability model is used to describe it. Moreover, as suggested by some authors (Allcott, 2011b; Ward et al., 2011; COOPER, 2011), the opposite phenomenon is also possible: a high-income consumer may invest in an efficient appliance "just" because it is the green option, also when the choice is not profitable from a strictly economic perspective. Thus, similarly as before, we assign a probability of purchasing the energy-efficient appliance when the investment is not profitable.

The curves in Figure 7.2 represent the probability of purchasing an energy-efficient product when economically profitable and when not. They are constructed partly based on the results from Allcott (2011b); Ward et al. (2011); COOPER (2011) and partly by using data about income and annual expenditure in appliances by households from Statistics Denmark (2016). The curves are employed as model assumptions as no empirical evidence for the functional slope is available in the literature. We also assume that the curves are not static but dependent on the specific appliance: if the NPV is positive but the payoff takes many years, then the blue curve shifts down, and vice versa. In the analysis we are not incorporating possible variations of the number of appliances and replacement rate by income class, and we equally split the stock among the classes.

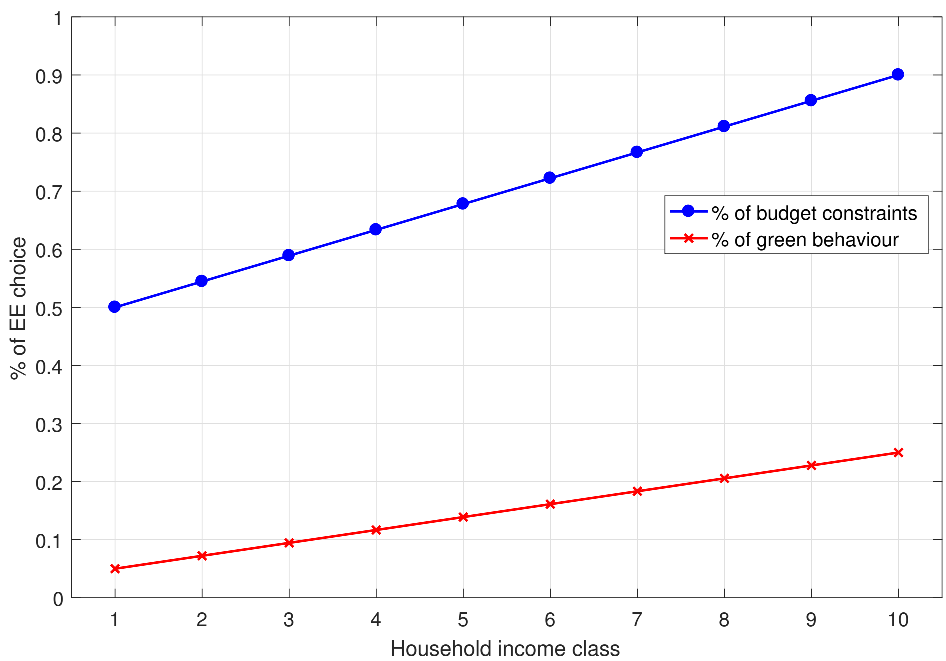

Figure 7.2: Probability of purchasing an energy-efficient appliance when economically profitable (blue line) and when not profitable (red line). On the x-axis are the deciles of the income distribution of Danish households.

In reality, the consumer choice is also subject to uncertainty regarding the information available (e.g. electricity prices and products on the market) and errors in computing the economic convenience. This uncertainty is already included in the consumer model, indeed, for instance, the adoption rate of profitable products by the highest income class is lower than 100%.

Coming back to the sequential approach, notice that also other authors have incorporated consumer classes (income deciles) with different behavioural profiles into a model which ultimately solves as a system optimisation, for example Bunch et al. (2015). We conclude the section with a few remarks.

1. After new electricity prices are generated, the end-user's model could be executed once again leading to a potentially different investment decision. This new decision could be plugged into the system model, and the sequential approach iterated until convergence (i.e. when there are no changes in electricity prices between two iterations). However, in all our experiments the model converged after the first iteration, thus we neglect the convergence topic in the following discussion.

2. In Eq.(7.4) savings are modelled using flexible electricity pricing. Even though most of the Danish households currently pay electricity based on a flat tariff (Energitilsynet, 2016), in the last few years smart meters have been spreading, reaching almost 50% of the of the Danish households in 2015 and aiming at 100% for 2020 (Danish Ministry of Energy Utilities and Climate, 2013; Danish Ministry of Energy Utilities and Climate, 2014). With smart meters and exposition to real-time rates, the adoption of flexible pricing is expected to quickly increase (Allcott, 2011a; Katz et al., 2016; Katz, 2014; Krishnamurti et al., 2012; Broman Toft et al., 2014; Faruqui et al., 2010).

7.3 Case study

The proposed model extension has been tested on the Danish energy system. However, the test is non-exclusive and the same analysis could be performed on a different system, provided that all the input data needed to run the model is available.

7.3.1 Scenarios description

We characterise the scenarios based on three main elements on the input side: simulation year, fuel price forecast and fuel availability. Two different simulation years are considered:

- **2015**: serves as an ex-post analysis to understand how the known energy system would have changed if consumer (or society) had invested in EE in an optimal way. For this case, the system is fully determined exogenously and we do not allow investments in new power plants. Thus, the model is in an operational simulation mode.

- **2025**: to assess the saving analysis on a future energy system. For this case, the energy system is also allowed to evolve by endogenously investing in new power plants and decommissioning the old and unproductive ones.

To cope with the uncertainty in fuel and emission prices in 2025, following Zvingilaite (2013) we identify a range of price values presented in Table 7.2: from a *low price* scenario to a *high price* scenario. The low price scenario has been constructed with the guidelines of the Danish Energy Agency for future socio-economic analyses (Danish Energy Agency, 2016b). The high price scenario is based on the oil price development in Oilprice.com (2016) and IEA (2016), with the assumption that the high prices for other fuels follow the price of oil with certain elasticity, as indicated e.g. in Karlsson and Meibom (2008). The cost of municipal waste is assumed to be negative and constant, since in Denmark the waste incineration plants are paid to treat the waste (Münster, 2009). Regarding CO_2, the low price scenario is based on the carbon trading price, which in fall 2009 was around 15 EUR/t (Reuters, 2016), whereas the high price scenario is based on the IPCC considerations (Ipcc, 2007). In the table we also report the average price scenario.

Table 7.2: Prices of fuels and emissions in 2025 according to different scenarios. Prices for renewable sources, e.g. wind, sun and hydro, are assumed to be zero.

	Low price [EUR/GJ]	Average price [EUR/GJ]	High price [EUR/GJ]
Fuel oil	13.33	17.24	21.14
Natural gas	12.01	15.02	18.02
Municipal waste	-3.60	-3.60	-3.60
Coal	5.05	6.97	8.89
Wood pellets	12.25	13.03	13.82
Straw	7.69	8.47	9.25
CO_2 [EUR/t]	18.02	39.04	60.07

In addition, we model availability constraints on the main input fuel sources for 2025. The limitations are decided according to the *4 degree scenario* proposed by the IEA in the Nordic Energy Technology Perspective (IEA, 2016). Table 7.3 reports the most relevant values.

Table 7.3: Fuel availability for 2025 (fuel input for power, heat and CHP plants), NETP (IEA, 2016)

	DK	SE	NO	FI
Coal [PJ]	99.2	9.4	0.0	87.8
Oil [PJ]	1.9	4.4	0.1	1.7
Gas [PJ]	21.4	3.6	0.0	34.8

The scenarios are tested using four representative weeks of the year (week 09, 22, 32, 51), where each week is composed by the full hourly resolution (168 hours), giving a total of 672 time steps for the simulation. In this way, we are able to obtain sufficiently accurate results, keeping the size of the model and its running time limited. The hourly resolution is needed here to entirely capture the differences of consumption profiles of the various home appliances.

7.3.2 Relevant parameters

A set of input data for each of the two Danish electricity zones must be collected. In Table 7.4 we report some of the most relevant parameters along with the reference.

Table 7.4: Relevant model parameters: values and references

Data	Zone	Value	Source
Electricity demand [TWh]	DK-E	13.70	NordPoolSpot (2016)
Electricity demand [TWh]	DK-W	20.44	NordPoolSpot (2016)
Number of households [mln.]	DK-E	1.15	Statistics Denmark (2016)
Number of households [mln.]	DK-W	1.41	Statistics Denmark (2016)
Electricity tax addition [EUR/MWh]	DK	265	Energitilsynet (2016)
Discount rate	DK	3%	Danmark NationalBank (2016)
Rebound effect	DK	3%	Nassen and Holmberg (2009)

Nowadays, the risk-free investment rate in Denmark is very close to zero (Danmark NationalBank, 2016). However, in our analysis we also account for the expected uncertainty from EE investments (given e.g. fuel price volatility and regulatory uncertainty). Therefore, ρ is increased and set equal to 3%, like the value used in Zvingilaite (2013) for heat saving investments in Denmark. The magnitude of the rebound effect related to EE, a debated topic in the literature, can vary from moderate to negligible levels depending on the analysis. In our model we use a rebound effect level of 3% related to household electric appliances (Nassen and Holmberg, 2009). The tax addition to the electricity system price in Denmark is estimated to be 265 EUR/MWh according to Energitilsynet (2016), and is expected to remain stable in the near future.

7.3.3 Appliances data

We selected the subset of 11 home appliance categories listed in Table 7.5. This set is chosen for several reasons. First of all these devices, together, constitute approximately

80% of the electricity demand of the private household sector in Denmark, hence they are the most interesting to study from an energy consumption perspective. The electricity demand of residential air-conditioning systems, for instance, is negligible in the Danish context and such appliance is therefore excluded from the study. Second, given the high energy consumption of the chosen appliances, the price of purchasing a new product reflects in a good extent its efficiency: when buying e.g. a new refrigerator of a given volume, the energy use of the product is typically the main factor driving the choice. On the other hand, for more high-tech appliances such as desktops, laptops, printers etc. this is generally not true and price difference between two products or brands is given by the functionalities rather than the consumption. Third, most of the selected appliances fall under the EU energy labelling program, therefore it is easier to collect the relevant data and assess the relationship between price and efficiency.

Table 7.5: List of household appliances considered in the analysis. The second and third columns refer to the annual consumption reduction and extra cost with respect to an average consumption class.

Appliance category	Saving [kWh/y]	Δ cost [EUR]	lifetime [years]
Stand-alone refrigerator	50	413	15
Stand-alone freezer	88	138	20
Refrigerator-freezer	152	605	17
Washing machine	109	242	12
Dish washer	65	572	10
Dryer	118	605	13
Lighting living room	29	9	6
Lighting secondary rooms	25	9	7
Cooker	52	435	12
TV LCD	24	243	7
Vacuum cleaner	11	130	7

The saving and cost data in Table 7.5 are averages over different products and brands, but with same volume or size, taken from some of the major producers and retailers active in Denmark (Bosch, Siemens, Electrolux, Miele, Aeg etc.). In the table, cooker refers to both electric hobs and electric baking oven. The lighting system is split in two components to account for the different use: one main room (living room) with an higher usage and the other secondary rooms. The extra cost is generally rather high since we model investments in appliances with the highest available efficiency class (e.g. A++ or A+++). Limiting the investment analysis to Denmark, we assume there are no differences in the performance or cost characteristics of existing or new appliances between the two regions DK-E and DK-W.

The presented model uses linear cost-efficiency relations for appliances, i.e. the purchasing cost of an appliance grows linearly with the consumption reduction. In practice, there may be differences between the appliances and more complex cost-efficiency relations. However, the data collected supports the assumption that a linear fitting describes the relation sufficiently well for our purposes. Figure 7.3 illustrates the cost-efficiency relation for two sample appliances.

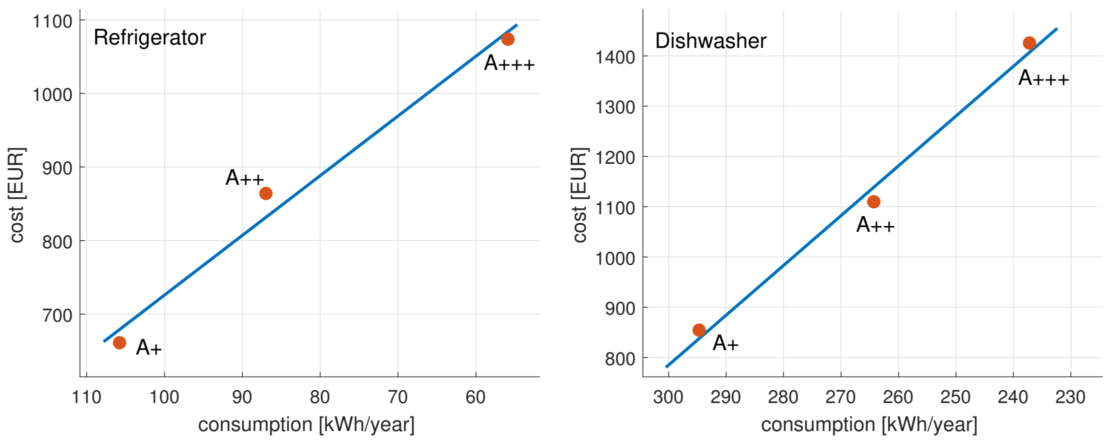

Figure 7.3: Cost-efficiency relations for refrigerators (left) and dishwashers (right), classes A+ to A+++. The dots represent average cost and consumption of a number of products of the same efficiency class, the blue line is the linear interpolation between them.

Regarding demand profiles, we rely on the results from Klinge Jacobsen and Juul (2015) who investigated the electricity consumption of a typical Danish household and determined consumption profiles for each appliance category. The profiles of the 11 appliances included in the analysis are illustrated in Figure 7.4, summing DK-E and DK-W.

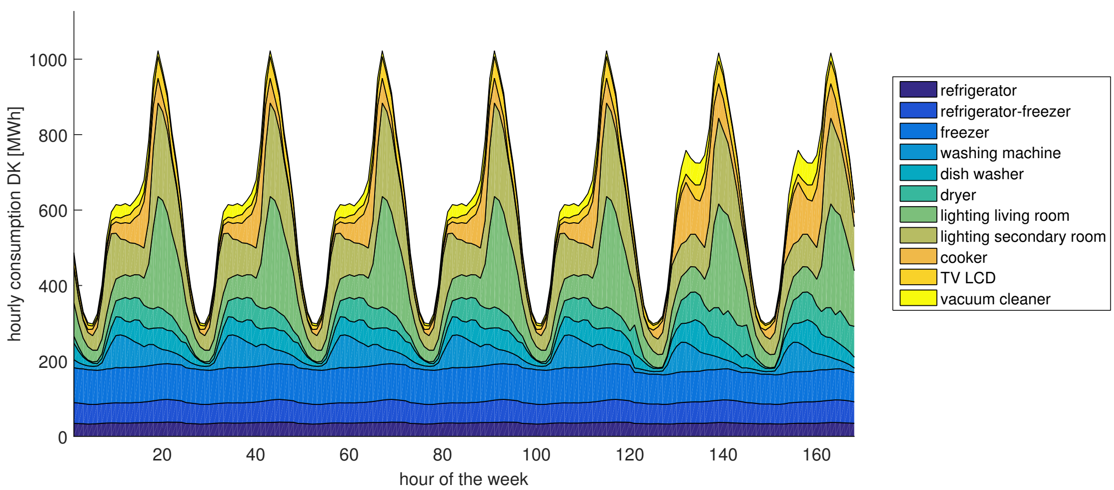

Figure 7.4: Electricity consumption profile during a sample week (week 09) of the 11 home appliances included in the analysis.

As expected, the profile changes considerably between the different categories. For example, the *cold appliances* (refrigerator, freezer) manifest a fairly flat profile while other appliances like lighting more contribute to the peaks, especially during the evening hours. Differences can be also found between working days and weekend: in the weekend the kitchen equipment is used more, in particular during lunch hours, and the use of the vacuum cleaner is higher too.

In Figure 7.5 we show how the aggregated profile of the 11 appliances contributes to the total electricity demand of households and of all sectors in Denmark.

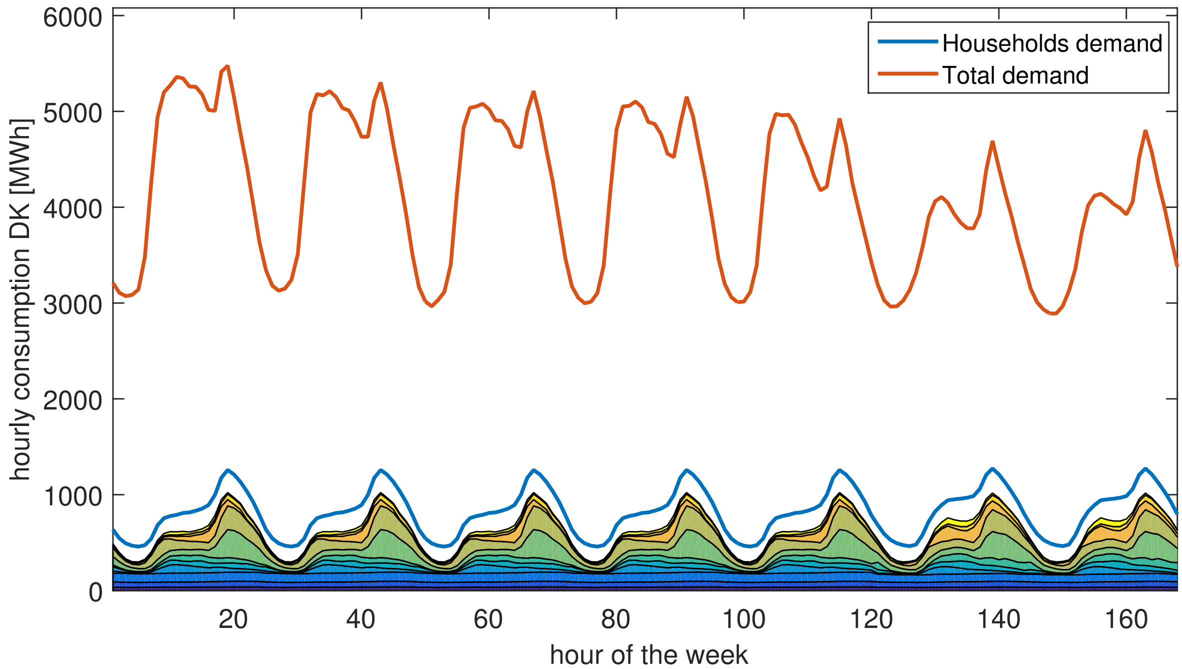

Figure 7.5: Aggregated profile of the 11 appliances compared to the total electricity demand in a sample week (week 09)

7.4 Results and discussion

A sensitivity analysis of the model using fuel and CO_2 costs for 2025 reported in Table 7.2 was made, resulting in similar electricity prices p_{rt} (although a different capacity mix is installed). This limited local sensitivity to scenario prices occurs because, given the replacement rate, only a small component of the energy demand is affected by the EE investments. As a consequence, we noticed no or very little change in the consumer choices (but different CO_2 implications) and, throughout the section, we will present the results for the average cost scenario for 2025.

7.4.1 Preliminary check

The driver for the investment choice lies in the economic profitability of adopting a particular appliance, based on the cumulative savings achieved during its entire lifetime. To get a first idea of the potential of investing in the different appliances, in Figure 7.6 we compute the amount of energy per unit that could be saved if an EE investment of 1 EUR is made in one of the examined appliances.

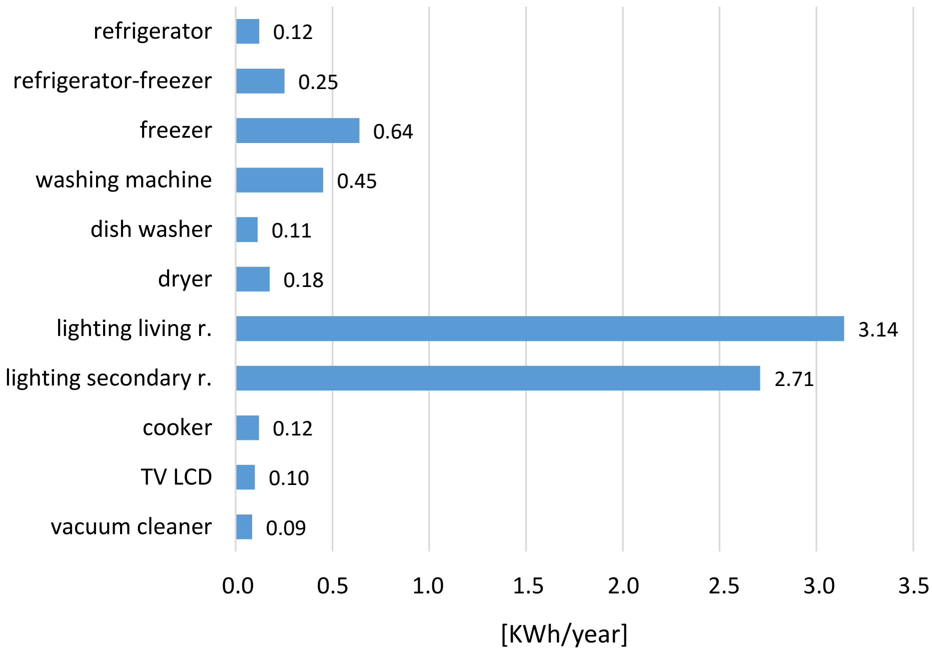

Figure 7.6: Annual electricity saving per 1 EUR investment.

As can be seen, the gap between lighting and other appliances is large: investing 1 EUR in lights results in an annual saving of around 3 kWh, while for other appliances it ranges from 0.1 to 0.6 kWh, i.e. an order of magnitude lower. Excluding lighting, from the picture it emerges that freezer and washing machine provide the best saving per unit investment, compared to the rest of the stock. Although Figure 7.6 gives a picture of the potential benefit of investing in the different devices, the final investment choices also depend on the hourly electricity price and the consumption profile of each specific appliance.

7.4.2 EE investments

The investments in EE appliances resulting from the simulations are shown in Figure 7.7. The left graph illustrates the optimal levels when the system model with endogenous investments is used, whereas the right graph represents the consumer choices after the sequential model is run. In the following, the values for DK-E and DK-W are presented as merged, even though they are separate zones from a model logic.

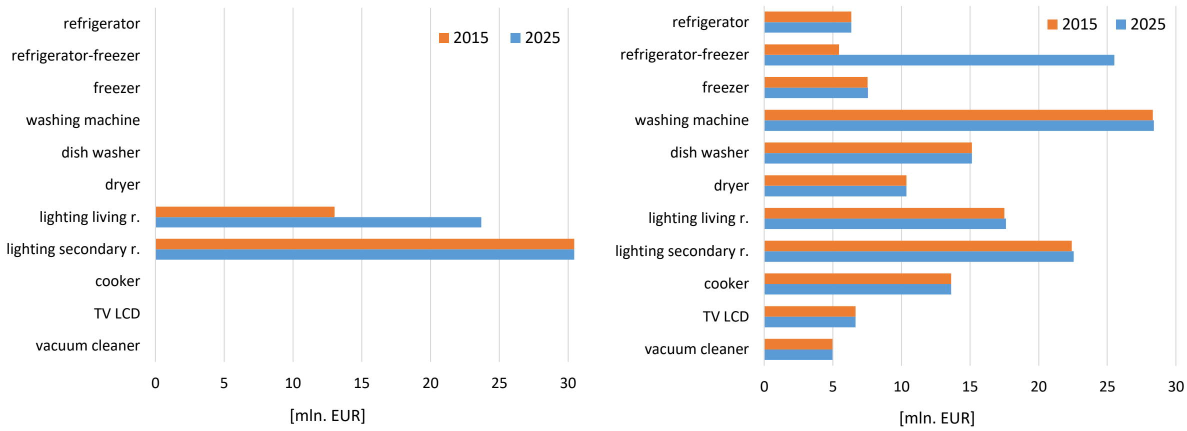

Figure 7.7: Investments in efficient appliances with the system model (left) and consumer model (right). The amount on the x-axis corresponds only to the extra cost with respect to the baseline efficiency class, and not to the overall investment cost in new appliances.

When the system is considered, the economic/energy saving criterion shows that the only EE investments worth doing are efficient lighting replacements. For 2025, the investment level in lighting for the living room is higher than 2015 due to the corresponding higher system prices of electricity for that year. This price difference develops because the system prices for the future energy system include long-term investments in renewable technologies and other system adjustments. Finally, given the lower saving per unit cost, no investment in other EE appliances is triggered during the optimisation process.

In contrast, the end-user economic convenience is based on the consumer electricity price and more diversified investments occur. Due to the consumer's behavioural dimension and the incompleteness of information, however, not all investments with positive NPV are undertaken and, vice versa, some investments in appliances with negative NPV occur. For instance, the investment level in lighting for secondary rooms (NPV > 0) are lower than 100% (as they are in the system model), and some investments in EE refrigerators (NPV < 0) take place. The consumer investments in EE exceed the system investments by 95 mln. EUR in 2015 and 105 mln. EUR in 2025.

Overall, the two years investigated show small differences in consumer choices, and investments in 2025 are only slightly higher than 2015. Indeed, even if the system prices of electricity are higher in 2025, the additive nature of the tax component makes the difference perceived by consumers less pronounced. The combined refrigerator-freezer represents an exception, in fact, the NPV becomes positive for some consumer classes between the two years, leading to a substantial increase for 2025.

To better understand the results, in Figure 7.8 we compare the lifetime of a new and more efficient household electric device with the Discounted Payback Period (DPP) of its extra investment cost, i.e. the time needed for the EE investment to break even.

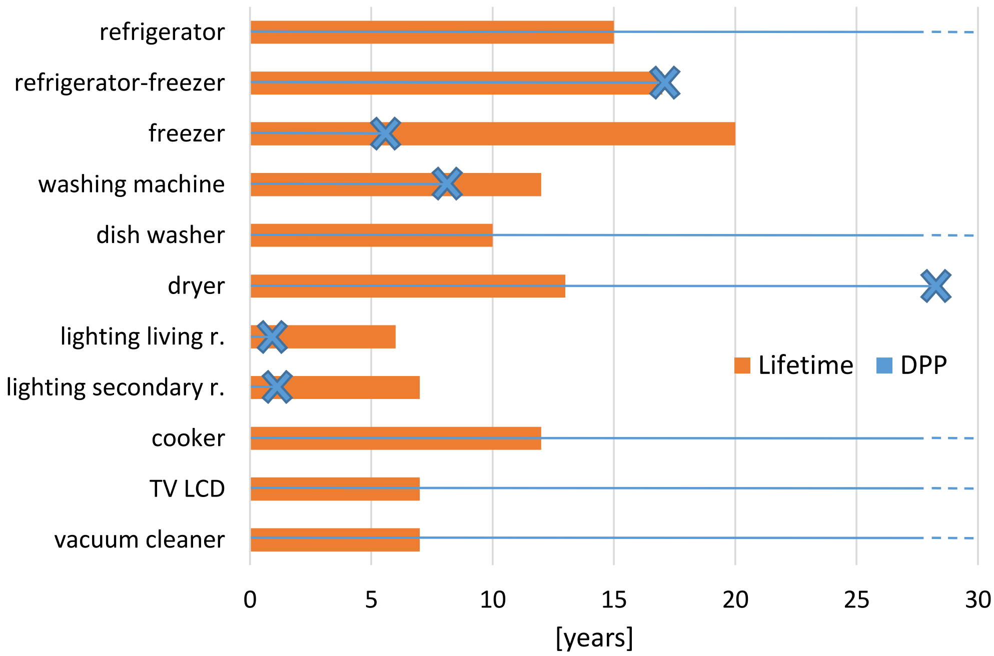

Figure 7.8: Lifetime vs. Discounted payback period (discount rate 3%) in the consumer perspective.

As can be seen, the DPP of an efficient lighting is approximately 1 year, for freezer and washing machine it is about 5 and 8 years respectively and for all other appliances it is longer than 15 years. For a rational consumer with no liquidity constraints, an investment is deemed worthy if the DPP is lower than the lifetime of the appliance, meaning that the appliance will be paid-off before the end of its expected lifetime (this is the same to having a positive NPV). The analysis shows that this criterion applies for lights, stand-alone freezers, washing machines, and combined refrigerator-freezers which are at the borderline. Specifically, one can notice that, although similar savings can be achieved with efficient washing machines and dryers (Table 7.5), the investment profitability differ substantially. Indeed, the most energy-efficient dryers are still very expensive, and the extra investment cost is higher than washing machines. Moreover, among the cold appliances, we notice that the profitability of EE freezers is higher than EE refrigerators.

In Table 7.6 we report the details of the investments, quantifying the adoption and effectiveness of energy-efficient appliances. Consider for instance 2015: with an up-front extra cost of 138 mln. EUR, the resulting energy and economic savings is 141 GWh and 41 mln. EUR per year respectively. Including the lifetime of the appliances and the discounting, this translates into revenues of 222 mln. EUR, i.e. a net discounted saving equal to

84 mln. EUR for Danish consumers investing in energy-efficient appliances (similar for 2025). In Table 7.7 we report the analysis of the benefits on the consumer side, highlighting the annual economic and energy savings resulting from the investments. The saving for 2025 is slightly higher because of the higher electricity prices. Notice that the saving is spread over the entire Danish population, disregarding the fact that only a portion of it is actually replacing a given appliance.

Table 7.6: Summary table for the scenarios analysis, 2015 and 2025

	investments [K units]		Investments [mln. EUR]		Economic savings [mln. EUR]		Electricity savings [GWh/y]	
Appliance	2015	2025	2015	2025	2015	2025	2015	2025
Refrigerator	15.4	15.4	6.3	6.3	0.22	0.25	0.77	0.77
Refr.-Freez.	9.0	42.2	5.5	25.5	0.40	2.13	1.37	6.42
Freezer	54.6	54.7	7.5	7.6	1.39	1.60	4.80	4.82
Wash.Mach.	117.0	117.3	28.3	28.4	3.71	4.33	12.76	12.79
Dish washer	26.5	26.5	15.1	15.1	0.50	0.58	1.72	1.72
Dryer	15.4	15.4	10.4	10.4	0.53	0.61	1.81	1.81
Light L.R.	1892	1904	17.5	17.6	16.00	19.03	54.87	55.23
Light S.R.	2423	2438	22.4	22.6	17.67	20.97	60.57	60.95
Cooker	31.4	31.4	13.6	13.6	0.47	0.56	1.63	1.63
TV-LCD	27.4	27.4	6.7	6.7	0.19	0.22	0.66	0.66
Vacuum Cl.	38.4	38.4	5.0	2.2	0.12	0.14	0.42	0.42
Total	4650	4711	138.3	156.0	41.2	50.4	141.4	147.2

Table 7.7: Average electricity and economic saving for Danish households

Year	Extra-investment costs [EUR]	Annual electricity saving [kWh/y]	Annual economic saving [EUR/y]	Net economic saving [EUR/y]
2015	54.0	55.2	16.1	32.5
2025	62.0	57.5	19.7	44.2

In the methodology section, we discussed the ability to afford investments according to the income class. In Figure 7.9 we illustrate the investment levels for each appliance disaggregated per class. The graph shows that the higher the income, the higher the share of the investment, reflecting the trends defined in the linear consumer model of Figure 7.2.

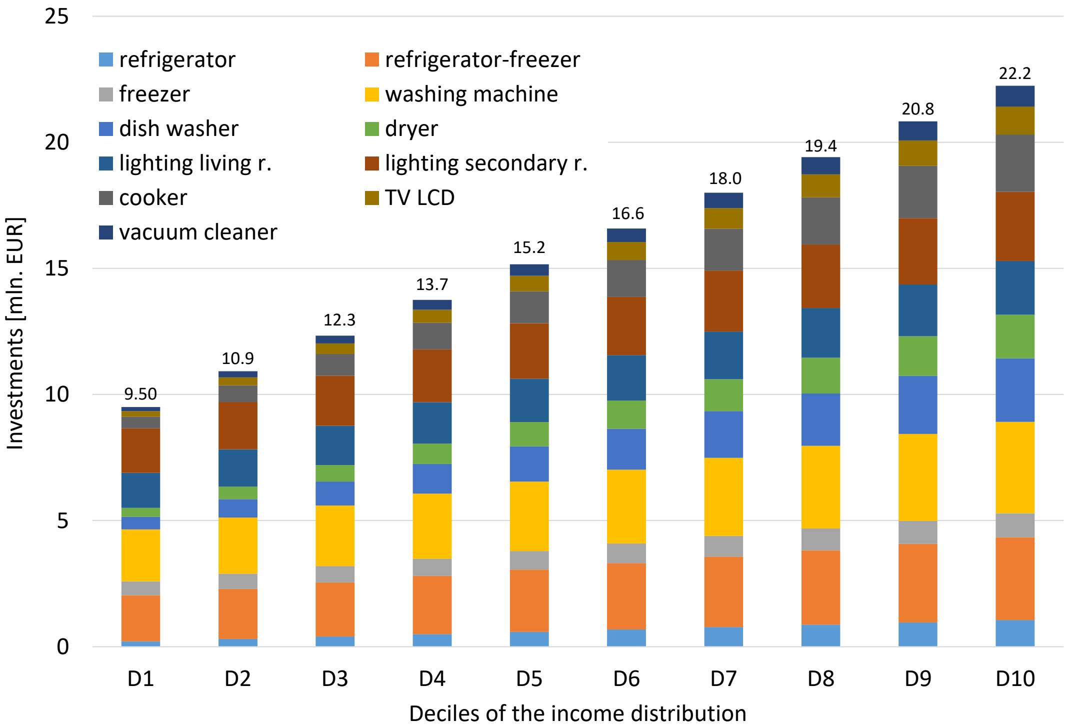

Figure 7.9: Investments in energy-efficient appliances according to the income class (2025)

7.4.3 System changes and comparison of perspectives

One of the main purposes of modelling the consumer behaviour is to determine its impact on the energy system. To assess the changes, we focus on two key parameters, CO_2 emissions and electricity demand reduction, and summarise the results in Table 7.8.

For 2015, we notice that introducing a consumer model leads to higher electricity savings compared to the optimal system investments (141 GWh vs. 123 GWh). With the implemented savings, Denmark could cut its CO_2 emissions of almost 0.48% according to the consumer model. Although this percentage seems small, the reader should keep in mind that a similar saving will occur in the years succeeding the investment. Considering the lifetime of the appliances and the substitution rate of the yearly stock, the cumulative savings will result higher in the long-term.

A different configuration emerges for 2025 where the level of electricity savings achieved in both models is higher than 2015. Nevertheless, the total amount of CO_2 reduction is lower. Indeed, the future energy system in 2025 will be highly based on renewable energy sources, especially wind, and several fossil fuels power plants will be decommissioned by then. Although the emissions reduction is lower, we notice that in percentage we obtained

Table 7.8: Total electricity and CO_2 savings.

	Electricity savings			CO_2 savings		
	Amount [GWh]	% house-holds DK	% DK	Amount [Kton CO_2]	% System	% DK
2015 Sys	123	1.88	0.38	83.7	0.020	0.34
2015 Cons	141	2.15	0.43	117.2	0.030	0.48
2025 Sys	157	2.44	0.49	32.8	0.017	0.87
2025 Cons	147	2.29	0.46	19.2	0.010	0.51

a CO_2 cut of almost 1%, implying a larger impact of the savings on the system. Moreover, for 2025 the savings achieved are higher in the system perspective. Indeed, in the system model more investments in lights take place which, as shown in Figure 7.6, contribute more effectively to the electricity demand reduction.

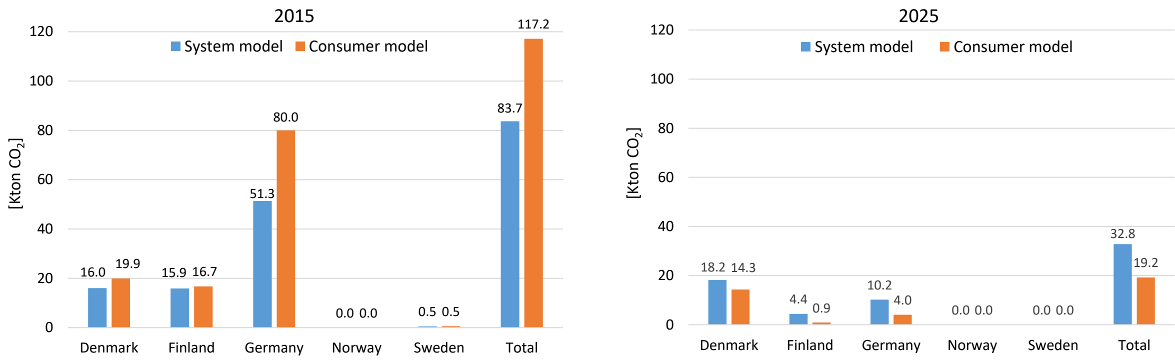

Figure 7.10: CO_2 emissions reduction in 2015 (left) and 2025 (right).

Figure 7.10 provides a graphical representation of the emissions reduction divided by country. It is interesting to see that, although a demand reduction via EE was implemented in the model only for Denmark, the decrease in CO_2 emission takes place in several other countries connected with Denmark. This highlights the influence of the interconnections between countries and proves that changes occurring in the Danish system has an impact on the electricity production not only of Denmark itself, but also of the other countries. For 2015, the largest emissions reduction occurs in Germany, where the simulation shows that future use of nuclear, natural gas, coal and lignite decreases while the power production from wind, wood pellets and municipal waste increases. Denmark comes after together with Finland; energy mix highly based on hydro and nuclear power, as Norway and Sweden, are not greatly influenced by small changes in the demand of a surrounding country. For 2025, instead, Denmark contributes more to the total CO_2 emissions reduction with 55% and 74% for the system and consumer perspective respectively.

The EE investments also affects the electricity consumption profile, as reported in Figure 7.11 for a sample week. The two different models, system and consumer, influence the demand in diverse ways. As can be noticed, the investments in the system model are entirely based on lights and mainly contributes to reducing the peaks. This is also in line with results from previous studies (Klinge Jacobsen and Juul, 2015). In contrast, being the consumer's investments more diversified, the demand is reduced homogeneously through the year, including hours outside peak loads.

Even though investments are generally higher and more variegated for the consumer model, the overall demand reduction is similar in the two cases. In fact, the slightly higher investment in efficient lighting for the system model results in total savings comparable to that of all the other appliances chosen by consumers together.

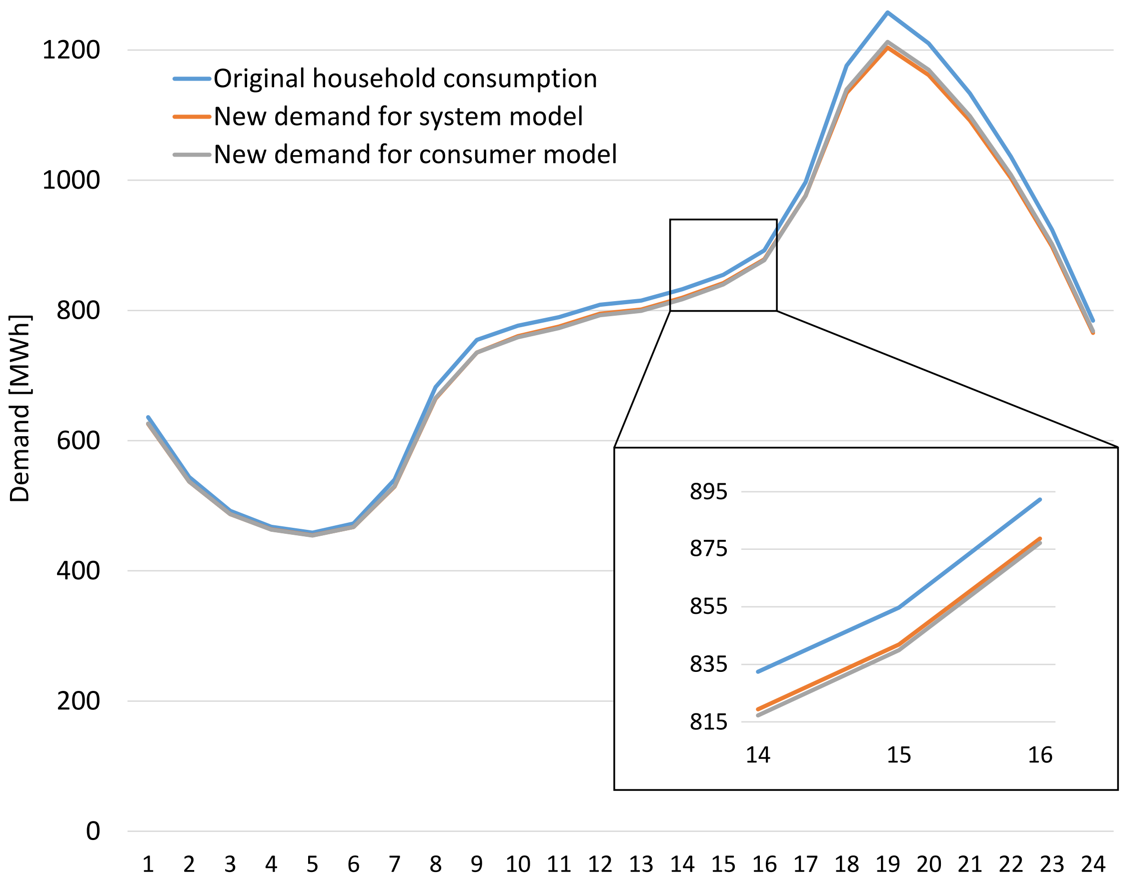

Figure 7.11: Electricity demand after system and consumer investment models (week 9, day 1).

7.5 Conclusions

The goal of this paper was to investigate the value of investments in more energy-efficient home appliances compared to a business-as-usual electricity supply scenario.

Two different perspectives have been examined: energy system and end-user. When the system is given the possibility to invest in efficient appliances, only investments in the lighting sector take place. In contrast, when the consumer has the choice, the investments are more diversified and generally higher. This highlights the different selection criteria for the two models: the system considers purely economical convenience, whereas for consumers a behavioural dimension comes into play. Moreover, two main factors have been considered when modelling the choices of the end-users: economic profitability and "green investments" propensity according to the income class. This last component, together with the different electricity prices, represents the reason for the diverse investments compared to the system perspective.

The findings presented in the paper are the result of a soft-linking between a well-known energy system model and a consumer-behaviour model designed for the study. The interactions between the two models is the key for understanding the impact of the consumer choices on the energy system. When compared to a business-as-usual energy scenario, with the investment solution resulting from the model, the end-user ends up on average with a net economic savings in the range of 30 - 40 EUR per year. Moreover, the system benefits of a total electricity savings of 141 GWh in 2015 and 147 GWh in 2025, and CO_2 emission reduction of 117 Kton in 2015 and 19 Kton in 2025. Because of the international interconnections and energy markets, changes in the energy system (e.g. in installed capacity, fuel consumption, emissions) occur not only in the country the consumer belongs to, but also in the surrounding countries. The decision of a single consumer, thus, contributes to the diversification and transformation of the global energy system.

The study also reveals the potential appliances that will be attractive from a system perspective and, despite the simplicity of the consumer choice model, it provides a first indication of the profitability of investments for private consumers. The closing considerations have highlighted the relevance of this analysis for a country that is aiming at important targets in terms of environmental issues. Therefore, this study should be pushed forwards.

7.5.1 Future Work

The presented study could be extended in several key directions. One way is to include a more sophisticated consumer behaviour into the investment decision function. The data from a survey conducted from the Danish Energy Agency[1] over a representing set of houses serve as the starting point for the new thorough analysis. Using this dataset, an exclusive, latent class logistic model could be employed to categorise the consumers into subsets with respective propensities to purchase (Shen and Saijo, 2009; Murray and Mills, 2011; Mills and Schleich, 2010). This could also help to better assess the functional slope of the purchase propensity by income class proposed in this paper. Using different discount rates could also be a natural way to incorporate several of the behavioural differences that are noted between consumer income classes. Of additional interest, Danish specific data and appliance purchasing behaviour is currently under investigation by UserTEC (2016) and could potentially be included. The end goal intended is then to incorporate the consumer categories into Balmorel to compute a more realistic energy savings scenario.

Additionally, this analysis can be extended to re-examine the efficacy of Denmark's imposed policies (i.e. EU driven energy labelling program and overall energy efficiency targets). Analyses in 2013 (Danish Energy Agency, 2016a) predicted savings of 5640 GWh/year by the year 2020 as a result of ecodesign requirements and the labelling program. With updated data on actual adoption, these projections can be reexamined. Additionally, these propensity estimates can inform investigation into the potential benefits of energy-efficient appliance support schemes.

Another avenue could be to explore the interaction and/or trade-off between reduced consumption and smart consumption. Indeed, in a decentralised system, EE means not only energy consumption reduction anymore, but also smart energy consumption. Denmark is still committed to equipping every household with a smart electricity meter by 2020. Despite much interest in intelligent demand response, such a sporadic system could diminish the service aspect of energy use. Thus, a comparative analysis into the savings provided by smart use vs. efficient investment could be explored via Balmorel.

Acknowledgements

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[1] At the time of the article writing (October 2016), this data is not available and is expected to be released in the upcoming months.

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Chapter 8

The impact of socioeconomic factors in the purchase of household energy efficient appliances: a case study for Denmark

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Abstract: Increasing the share of evermore energy efficient household electric appliances is one strategy to address environmental impacts arising from residential electricity demand. Hence, governments and energy actors are interested in the determining factors behind the consumer choice of conventional versus high efficiency labelled appliances. This study employs empirical survey data from the Danish Energy Agency to model influential factors behind Danish consumer choice of energy efficient appliances. To estimate consumer propensities, we use a logistic regression model over a set of socioeconomic, demographic, and behavioural variables. The study regresses over this unique combination of end-use behavioural variables by creating an energy efficiency index. Statistical results show that housing type, quantity of inhabitants, age, and end-use behaviour are strong predictors for choosing energy efficient appliances. Interestingly, income is a weaker predictor. Despite a relatively wealthy national income and well-educated population, information campaigns have been largely ineffective in driving high efficiency investments. In light of this study's results and exogenous factors such as urbanising demographics and shifting Danish housing stock towards apartments, the study suggests improved information campaigns by targeting key demographics.

Keywords: Consumer behaviour · Energy efficiency · Household appliances · Purchase propensity · Regression model

8.1 Introduction

Like other Western European nations, Danish household electricity consumption accounts for more than 20% of total electricity demand (Gaspar and Antunes, 2011). Electric devices such as dishwashers, washing machines, cooking hobs, microwaves, fridges and freezers account for 50% of this figure (FEHA, 2017). The quantity of household appliances, due to rising wealth and access to technology, has increased dramatically over the last decades according to the Danish Association for Suppliers of Electrical Domestic Appliances (FEHA).

In 1992, the European Union (EU) addressed rising household electricity demand and its environmental impacts with the EU Directive 92/75/EC establishing the energy consumption labelling scheme for most white goods and light bulbs (EU, 1992). Its aim was to increase consumer awareness of energy consumption by demanding clearly visible labels classifying electric devices from the most energy efficient (Class A) to the least (Class G). Since 1995, EU consumers have been exposed to this letter-grade labelling system. Given increasing appliance energy efficiency, the EU extended the labelling system with Directive 2010/30/EU by introducing classes A+, A++ and A+++, and is planning to rescale the metric to the A-G scale in the future (see (EU, 2015) and (EU, 2017) for details).

In light of EU energy saving efforts, the purchasing propensity for EE (energy efficient) appliances, coupled with efficient end-use, now carry greater importance. The drivers of appliance purchasing are diverse: short and long run household economics, attitudes towards the environment, and casual choice, among others. By addressing these factors, governments may improve efficiency standards and labelling campaigns. Due to their diverse nature, though, leveraging these factors and estimating their effect on appliance purchasing might be challenging. Data from surveys assessing consumer preferences could represent an initial valuable source of information while tools like consumer choice models, for instance, could help drawing considerations about purchasing choices.

Our study is motivated by the following research questions. Which socioeconomic characteristics best predict the consumer selection of high-labelled household appliances? What impact has the end-user behaviour, in relation to energy use and savings, on purchasing such household appliances? Which energy end-use daily actions are more relevant for predicting the purchase of appliances? Accordingly, which polices can increase consumer consciousness of energy efficiency so as to adopt high-labelled household appliances thus reducing CO_2 emissions?

To address these research questions, we considered the results of a Danish Energy Agency (DEA) survey over a representative housing sample, and developed a logistic regression model to predict the propensity of the Danish consumer to choose a new, highest-labelled household appliance. In this model, we employed socioeconomic and demographic variables (e.g., income age, income and job of the consumer, housing type, size, year built, and number of inhabitants) as well as a behavioural energy efficiency variable (EE-index) calculated from a set of consumer energy end-use behavioural questions (e.g., turning off the power sockets during the night and adapting the heating system to the seasons). Based on the model results, we estimated propensities of Danish consumers to choose more efficient appliances at the moment of purchase. Eventually, we drew policy recommendations, relevant beyond the Danish context, to foster energy efficient behaviours and increase the purchase of EE appliances in the residential sector.

This paper contributes to the field by developing novel methodology resulting in practical findings that can be useful for policy makers and governmental institutions. On the methodological side, the contributions of the paper consist of (i) the construction of the EE-index that gathers and synthesises a rich set of consumer behavioural characteristics and daily actions regarding energy end-use and energy savings, and (ii) the integration of such index in a consumer choice model to study the joint effect of socioeconomic, demographic, and behavioural variables on consumers energy efficiency investment choices. Finally, unlike previous studies, (iii) we performed an extensive investigation of a behavioural index through correlation matrices and by examining interrelations between its constituent parts.

On the practical side, we find from our statistical results that socioeconomic and behavioural characteristics are highly significant when explaining the choice of purchasing EE appliances. Specifically, income, housing type, quantity of inhabitants, age, and end-use behaviour are predictors for choosing energy efficient appliances, with EE-index and housing type being the strongest of these predictors while income is weaker. From our analysis of the EE-index, we identify that specific daily actions are correlated with investment in efficient household appliances. Furthermore, by analysing the correlations within the EE-index, we found that respondents generalise their EE behaviour by appliance type and that efficient end-use behaviours are related with particular living conditions, e.g., housing type.

By providing empirical results on the influence of both socioeconomic and behavioural variables on consumer choice, the paper narrows the knowledge gap on household energy consumption behaviour and broadens knowledge on the drivers of purchasing high-labelled household appliances.

The remainder of the paper is organised as follows. In Section 8.2, we review the literature on household energy consumption behaviour. In Section 8.3, we introduce the survey data and describe the consumer investment model based on logistic regression. In Section 8.4, we present the model estimation results and discuss the effect of different socioeconomic, demographic, and behavioural variables in the choice of EE appliances. We conclude in Section 8.5 by drawing practical policy suggestions based on our findings.

8.2 Literature review

The study of household energy consumption behaviour focuses on understanding the reasons why end-users adopt particular consumption patterns. Four key questions are the focus of debate: (1) What is driving energy consumption; (2) How does lifestyle and habits influence the use of energy; (3) Which models can closely describe the consumer behaviour; and (4) Which policies can be proposed to decrease total energy use.

Socioeconomic characteristics are often cited as significant drivers of household energy consumption. Global research programs, conducted via household surveys, suggest that demographic and socioeconomic factors, such as income level, ownership, dwelling type and number of inhabitants, are correlated with the energy use (De Almeida et al., 2011; Bedir et al., 2013; Wyatt, 2013; Zhou and Teng, 2013; Hayn et al., 2014; Huebner et al., 2015; Murphy, 2014; Jones and Lomas, 2016; Zhou and Yang, 2016; Girod et al., 2017).

Beyond these factors, researchers stress the focus on energy consumers' end-use behaviour. Lifestyle and habits impact the final use of energy, most often in an unpredictable way (Zhou and Teng, 2013; Gram-Hanssen, 2014; Frederiks et al., 2015). Empirical research indicates that behaviour (or comfort preference) is related to the socioeconomic characteristics, including income (Vassileva et al., 2012), household type (Bedir et al., 2013; Huebner et al., 2015; Jones and Lomas, 2016; Girod et al., 2017), family age composition (Mills and Schleich, 2012), and employment (Hayn et al., 2014). Additionally, ulterior motives influence behaviour such as environmental consciousness (Gram-Hanssen, 2014; Zhou and Yang, 2016), environmental innovation intention (Long et al., 2017b) and attitude towards environmental behaviour (Long et al., 2017a) which, ultimately, has an impact on consumer's intentions (Ajzen, 1991; Abrahamse and Steg, 2009).

The aforementioned socioeconomic and behavioural characteristics are also studied as relevant reasons prompting consumers to choose high-labelled appliances. The results from a 2014 Organisation for Economic Co-operation and Development (OECD) survey on household environmental behaviour and attitudes identified potential factors behind consumer choices on energy efficiency investments as home ownership, income, social context, and household energy conservation practices (Ameli and Brandt, 2015). Various analyses, based on different surveys in an international context, resulted in similar conclusions (Mills and Schleich, 2010b; Gaspar and Antunes, 2011; Qiu et al., 2014; Jacobsen, 2015). In the Danish context, although previous studies have used survey results to assess the factors influencing household electricity consumption (Bartiaux and Gram-Hanssen, 2005), efficient utilisation of household appliances (Nielsen, 1993), and patterns of domestic electricity use (Gram-Hanssen et al., 2004), to the best of our knowledge none has focused on purchase propensities in relation to energy efficient household appliances. Moreover, while other studies made use of energy-related behaviours and habits in consumer models (Gaspar and Antunes, 2011; Kavousian et al., 2013; Krishnamurthy and Kristrom, 2015; Ameli and Brandt, 2015), none has performed an extensive investigation of such energy end-use behaviours. In fact, in this paper we analyse interrelations among various behavioural components to investigate which actions make the consumer more likely to invest in EE appliances and if specific end-use behaviours are related to particular living conditions.

The science of consumer behaviour and energy literacy–that is, the ability of consumers to make rational decisions on EE investments (Brounen et al., 2013)–adopts and employs energy efficient behavioural measures, equipment, intentions and planned behaviour (Abrahamse and Steg, 2009; Ajzen, 1991; Long et al., 2017a). Often, when designing appropriate tools, the economic theories on consumer's choices are based on rational maximising models describing how consumers should choose (normative theories) rather than how they do choose (descriptive theory). Results from orthodox-economic models where the consumer is depicted as a robot-like expert, can thus be a poor prediction of the actual behaviour of the average consumer (Thaler, 1980). Realistic empirical studies provide evidence that consumers don't always act rationally and their choices are influenced by a myriad of non-rational influences. Thus, consumer behaviour models, if wrongly formulated, can lead to misleading outcomes (Thaler, 1981). Realistic consumer behaviour is crucial when designing proper tools for predicting or describing consumer choices. With this in mind, in this paper we built a logistic regression model–validated using different statistical tests–that accounts for socioeconomic and demographic variables as well as behaviours, trying to capture non-rational influences on consumer choices. This model provided us with interesting insights on the characteristics influencing the decision process of the consumers when purchasing high-labelled household appliances.

Studies investigating the success of policies implemented, such as the ENERGY STAR in the U.S. or A-G energy labels in Europe, show that financial incentives (subsidies), energy audits, minimum energy performance standards (MEPS), energy literacy and reduced value added taxes for EE technologies contribute positively to the uptake of energy efficient appliances and replacement of old equipment (De Almeida et al., 2011; Mills and Schleich, 2012; Brounen et al., 2013; OECD, 2013; Murphy, 2014; Krishnamurthy and Kristrom, 2015; Datta and Filippini, 2016; Zhou and Yang, 2016; Girod et al., 2017). Similar to MEPS, mandated energy efficiency measures (for new equipment) coupled with properly designed and implemented public awareness campaigns results in legitimate energy savings (Wyatt, 2013; Frederiks et al., 2015; Young, 2008). A recent analysis on the Danish market, for example, showed that new labelling schemes lead to a notable increase in the sales of EE appliances (Bjerregaard and Framroze Møller, 2017). However, in contrast, some of the literature on the efficacy of policies and information campaigns showed that a large portion of the population is still unaware of energy labelling (De Almeida et al., 2011; McMichael and Shipworth, 2013; OECD, 2013; Zhou and Yang, 2016) or energy conservation behaviour measures (Brounen et al., 2013). Finally, recent research has shown that policies and actions need be tailored to specific households, tenants and technologies since a generalised approach might not work as efficiently and lead to less than desirable outcomes (Vassileva et al., 2012; Frederiks et al., 2015; Krishnamurthy and Kristrom, 2015; Jones and Lomas, 2016; Chai and Samatha, 2017; Girod et al., 2017). Following this literature, in this paper we suggest improved energy efficiency policies that indeed target key demographics identified through our purchase propensity analysis.

8.3 Data and model

The primary dataset analysed in this study is the DEA's bi-annual survey "El-model Bolig", the goal of which was to collect information about consumers' purchasing and use of household appliances. Although the survey is performed every two years, the 2012 set was chosen over the most recent dissemination because the 2012 survey uniquely contains questions on the efficiency labelling of major household appliances. The total number of survey respondents, or observations, was 2053; however, we removed 337 observations due to missing values giving a final sample size of n = 1716. The survey comprises about 340 questions in total. The number of questions for each respondent, though, depends on logical operators and reported ownership–for instance, a respondent without a freezer will not be asked questions about its usage. The sampling was conducted under random block design as to approximately represent Denmark's geographic and housing category distributions (apartments, farmhouses etc.), and was not stratified with respect to other socioeconomic and demographic variables.

8.3.1 Socioeconomic, demographic, and behavioural variables

The primary variables of interest from the survey are the socioeconomic and demographic variables listed below, chosen with the intention of predicting investment in the highest EE labelling.

- Age: an ordered categorical variable whereby Age 1 = 18–29 years, Age 2 = 30–39 years, Age 3 = 40–49 years, Age 4 = 50–59 years, and Age 5 = 60 years or older.

- Quantity of inhabitants: recorded as a continuous variable in the original survey dataset, counting the total number of adults and children living in the respondents' household.

- Housing type: four choice levels given by apartment, farmhouse, single/detached (referred to as "single" henceforth), and townhouse.

- House size: an ordered categorical variable with 8 levels from less than $39\,m^2$ to over $200\,m^2$ interior floor space.

- Year built: an ordered categorical variable with 6 levels for the year a house/apartment was constructed, ranging from before 1900 to 2001 or newer.

- Income: gross household income (before taxes).

- Investments in EE appliances, that is, the labelling of most recent purchased appliance.

Beyond questions about appliance investment and ownership, the survey contains a wealth of questions regarding end-use behaviour for appliances and heating systems. Several of these questions can capture whether the consumer performs daily activities classifiable as energy efficient behaviour. Questions like "How full do you fill your clothes/washing machine on a normal use" or "Do you turn off the power socket during the night" have thus been used (see the Appendix 8.6.1 for the full list of questions included in the index). We incorporated these unique responses by computing a behavioural energy efficiency index, abbreviated throughout the paper as EE-index. The combination of these variables in the index represents a level of energy consciousness and intent to save energy for both electricity and heating. For example, managing heating between night and day (turn heat down at night) or removing power sockets after use are all positive EE indicators.

To compute the EE-index, we assigned each question an equally weighted point: 1 for positive energy saving behaviour, 0 for poor behaviour. Although in theory different actions can result in different levels of energy savings, the survey does not contain detailed appliance and action characteristics (e.g., appliance type, capacity, consumption, time of use) that enable directly quantified savings nor define action-specific weights. All questions are weighted equally with scores normalised per each respondent's appliance portfolio. Of course, not all respondents own oil or natural gas heating, for instance. Thus, to compare respondents with differing levels of appliance ownership, the individual scores were standardised by their individually maximum possible score (see the Appendix 8.6.1 for the percentage of respondents eligible for each question). The score is defined for each consumer $j \in \{1, \ldots, n = 1716\}$ in the sample as

$$\text{EE-index}_j = \frac{1}{Q_j} \sum_{i=1}^{\overline{Q}} Z_{ij},$$

where $\overline{Q}$ is the total number of questions, Q_j is the count of eligible questions for respondent j, and Z_{ij} equals 1 for a point awarded to respondent j for question i. Eligible questions Q_j are counted according to the appliance ownership profile of respondent j. For example, a respondent without a washing machine will not be scored nor counted in Q_j for questions pertaining to washing machine use. The index is on a $[0, 1]$ scale. Of course, more appliances (greater summed Q_j) will decrease the marginal weight of each point, that is, the index is less sensitive to those with many appliances or eligible questions.

The survey also contains additional questions regarding profession of respondent and spouse, lighting system and electricity consumption. In addition to the EE-index, we thus calculated:

- a "job index" whereby the respondents' professions were ranked per average years of training or education on a scale from 1 to 10 for the job categories included in the survey. This job index was then considered a potential predictor of EE appliance investment.

- a "light score" assessing the respondents' ownership of EE lighting. The light score is calculated as the ratio of reported saving light bulbs, or EE lighting (for instance, LEDs and compact fluorescent lamps), to the total sum of both EE lighting and traditional incandescent light bulbs. Thus, the score is normalised on a $[0, 1]$ scale.

- the "know el.", representing a non-socioeconomic binary variable equalling 1 if the respondent reports to currently know her annual electricity consumption, and 0 if the respondent reports not knowing.

Table 8.1: Explanatory variable name, type, and description

Explanatory variable	Type	Description
Qty. inhabitants	continuous	Number of household inhabitants, from 1 to ≥ 8
House type	categorical	4 levels: apartment, farmhouse, single house, townhouse
House size	categorical	8 levels, from less than $39\,m^2$ to over $200\,m^2$
Year-built	categorical	6 levels, from < 1900 to ≥ 2001
Age	categorical	5 levels: 18–29, 30–39, 40–49, 50–59, 60 or older
Income	continuous	Gross household income, in $[0,+\infty]$
EE-index	continuous	Behavioural energy efficiency index, in [0,1]
Job index	continuous	Average years of education/training, in [1,10]
Light score	continuous	Energy efficiency lighting ownership, in [0,1]
Know el.	categorical	Knowledge of own electricity consumption, in $\{0,1\}$

In Table 8.1 we present a summary of the explanatory variables used in the model, and their characteristics. Lastly, we are interested in the investments in EE labelled appliances. The survey asked each respondent to state the energy labelling of a given appliance they report to own or which they had recently purchased. The full set of appliances in the survey are: combination washer-dryer, washing machine (standalone), dryer (standalone), dishwasher, combination fridge/freezer, fridge with integrated box freezer, fridge (standalone), chest-freezer, and a standing freezer. For some of the appliances (e.g., chest-freezer) too few respondents reported ownership, not allowing us to make a meaningful analysis per each individual appliance. Thus, the set is aggregated to a singular latent variable: "for her most recent purchase in any one of these appliances, has the consumer invested in the rating A+ or higher?" Because of such aggregation, 68% of respondents reported EE investment while 32% did not. The rest of the paper focuses on identifying which of the explanatory variables best distinguish these two groups of consumers. We first present descriptive statistics for the modelling sample and compare them against national statistics.

8.3.2 Dataset validation

To verify that our dataset provides a good representation of Denmark, we compared the distribution of the socioeconomic factors in our modelling sample against the 2012 national statistics from Statistics Denmark (DS; see (DS, 2017b)).

The age distributions of the survey sample and DS are displayed in Figure 8.1. The distribution of the survey sample is slightly skewed towards middle and elder ages since, typically, it is the head of the household who is answering the survey. This explains why age level 1 is only 7% of the survey sample while age level 4 is 32%. The remaining classes are similar to those of DS.

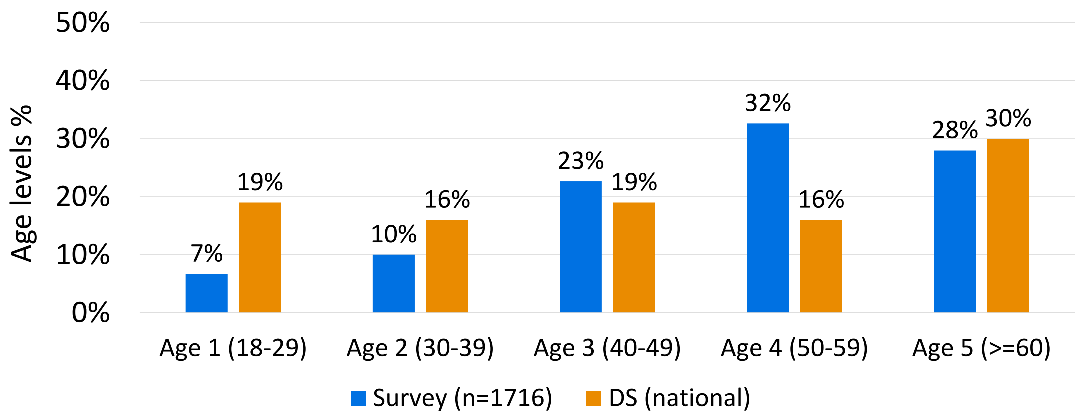

Figure 8.1: Age of respondents: survey sample and national statistics

The survey distribution of the number of inhabitants is displayed in Figure 8.2 and is deemed fairly representative. Some differences compared to the national statistics hold for one and two inhabitants per household, but overall are acceptable.

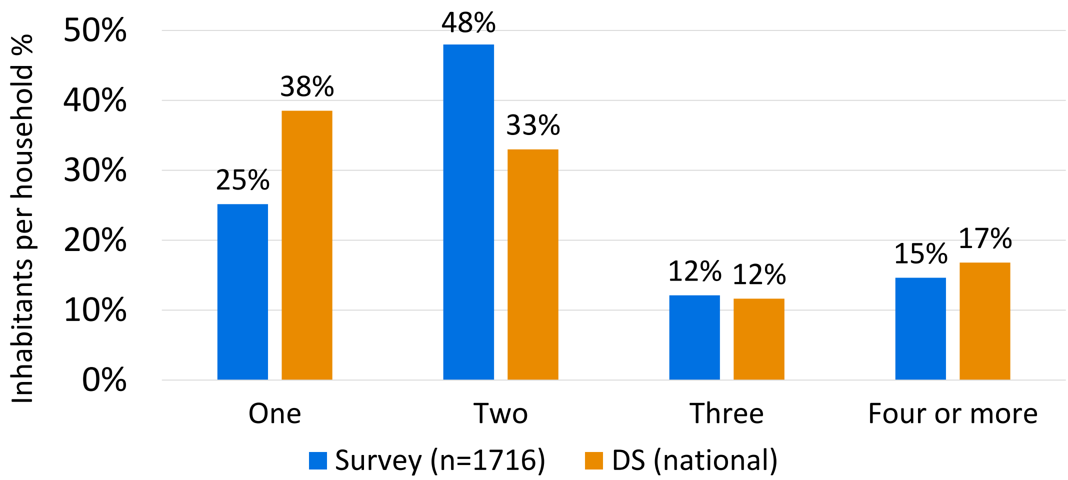

Figure 8.2: Quantity of inhabitants: survey sample and national statistics

Regarding housing age, Table 8.2 shows that the 2012 distribution of year built in the survey sample closely matches that of official registries, thus, it is representative of Denmark.

Table 8.2: Housing year built: survey sample and DS.

Year built	Sample	DS
Before 1900	8%	9%
1900-1925	11%	12%
1926-1950	15%	16%
1951-1975	34%	32%
1976-2000	25%	23%
2001 or newer	7%	8%

The variables for which a comparison was not possible include housing type and income. Regarding housing type, the categories used in the survey diverge from those recorded in the official statistics. For example, DS includes student housing and cottages, which are ignored by the survey. Moreover, DS includes some detached housing types in its farmhouse category, whereas the survey farmhouse category explicitly pertains to properties with land holding. As a consequence, a comparison between DS and the survey housing type distributions would be misleading. Regarding income, the survey originally reported the total household income before taxes, whereas DS reported the "disposable equivalised income", which is the household income after taxation divided by a weighted number of adults and dependents living in the given household (DS, 2015). Therefore, any comparison would be inaccurate due to the different income calculation and the inability to assume taxation rates on the survey's gross incomes and convert gross incomes into disposable incomes.

8.3.3 Consumer investment model

Consumer behaviour in relation to investments in household energy efficient appliances is evaluated with a discrete choice model. The merit of this modelling framework is the ability to empirically test the predictive strength of the survey's explanatory variables. Specifically, we use a logistic regression model that is constructed as follows. The EE investment is considered as a binary outcome Y (1 = investment, 0 = no investment) and the model assumes that

$$\begin{aligned}\operatorname{logit}(P(Y=1\,|\,X_1=x_1,...,X_n=x_n)) =& \log\frac{P(Y=1\,|\,X_1=x_1,...,X_n=x_n)}{1-P(Y=1\,|\,X_1=x_1,...,X_n=x_n)}\\ =&\beta_0+\beta_1x_1+...+\beta_nx_n,\end{aligned}$$

where $X=[X_1,\ldots,X_n]$ represents the vector of all explanatory variables discussed in Section 8.3.1 (age, income, type of house, EE-index etc.) and $\beta=[\beta_0,\ldots,\beta_n]$ the weight vector. The dependent variable Y represents a single investment in an A+ or higher labelled appliance among a set of nine appliances listed in the survey (the set of appliances is considered as aggregated to maintain an adequate sampling size and distribution, as discussed in Section 8.3.1).

To estimate the model, the weights β are fitted through logistic regression on the survey data via the logit maximum likelihood function. Then, given the estimates $\hat{\beta} = [\hat{\beta}_0, \ldots, \hat{\beta}_n]$ and the characteristics of a consumer $x = [x_1, \ldots, x_n]$, the resulting predicted joint-probability of EE appliance investment π, or the probability that $Y = 1$, is computed as:

$$\pi = P(Y = 1 | X_1 = x_1, ..., X_n = x_n) = \frac{\exp(\hat{\beta}_0 + \hat{\beta}_1 x_1 + ... + \hat{\beta}_n x_n)}{1 + \exp(\hat{\beta}_0 + \hat{\beta}_1 x_1 + ... + \hat{\beta}_n x_n)}.$$

8.4 Results and discussion

8.4.1 Model estimation

Table 8.3 reports the outcome of the multivariate regression consumer investment model, computed with the software R. The final regressors are chosen, according to common practice, using a backwards elimination process until the model only contains statistically significant explanatory variables (Derksen and Keselman, 1992).

*Table 8.3: Consumer investment model estimates. Significance codes for p-values: 0.001 '***', 0.01 '**', 0.05 '*', 0.1 '.'*

Explanatory variable	$\hat{\beta}$ estimate	Std. error	p-value	Significance level
Intercept	-2.001	0.295	< 0.001	***
Income	0.076	0.030	0.011	*
Light score	0.480	0.180	0.007	**
EE-index	0.762	0.303	0.011	*
Know el.	0.221	0.127	0.082	.
Qty. inhabitants	0.198	0.066	0.002	**
Farmhouse	0.673	0.230	0.003	**
Single house	0.550	0.142	< 0.001	***
Townhouse	0.304	0.173	0.079	.
Age group 2	0.674	0.267	0.011	*
Age group 3	0.683	0.245	0.005	**
Age group 4	0.712	0.242	0.003	**
Age group 5	0.849	0.244	< 0.001	***

The factor levels age group 1 and apartment are considered model reference levels and thus do not respectively have model terms. The joint probability for age group 1 and apartment is considered to be the estimate of the model intercept, or the probability of investing when all other variables are set to 0. One can see that the explanatory variables positively affect the total probability of EE investment choice. For example, assuming all other variables constant, by increasing income of one unit (100,000 DKK), the expected odds of choosing an EE appliance will be 1.079 times greater (since $\exp(0.076) = 1.079$).

The values in Table 8.3 represent the outcome of the final model only. Other explanatory variables, as house size or job of the respondent, were included in a previous larger model but discarded in the backward elimination process. Table 8.4 reports the dropped explanatory variables (that is, with p-values higher than 0.1) along with their $\hat{\beta}$ estimates. The dropped model estimates show that the year in which the building was built, the size of the households and the job of the respondent appear not to be relevant characteristics to predict selection of EE appliances.

Table 8.4: Consumer investment model estimates for the dropped explanatory variables.

Explanatory variable	$\hat{\beta}$ estimate	Std. error	p-value
Year-built	0.045	0.044	0.313
House size	0.005	0.032	0.867
Job index	0.014	0.017	0.410

The final model adapted for the analysis has been validated to prove the consistency of the findings and assess the reliability of the model. Different criteria have been used for model diagnostics:

1. The Hosmer-Lemeshow's Goodness of Fit test is widely used in logistic regression to prove the fit between the model and the data (Hosmer and Lemesbow, 1980). It tests against the null hypothesis H_0 of observed investment rates matching the predicted ones, and returns a p-value. A p-value lower than 0.05 suggests that the model does not adequately predict the binary outcome of Y and should be rejected. The outcome of the test was a p-value of 0.33, meaning there is no evidence to reject the model.

2. The McFadden R-squared test is similar to the R-squared test but based on the rho-squared measure (McFadden, 1977). The test returns a value representing the predictive ability of the fitted model compared to the null model, that is, a model with only an intercept and no covariates. According to the test, any result between 0.2 and 0.4 represents an excellent fit. The outcome for our model was a value of 0.21.

8.4.2 EE-index and light score

We summarise the most important variables in the EE-index composition in the form of a heatmap in Figure 8.3. The EE-index variables are divided by housing type and, for brevity, they are listed in their coded format (see the Appendix 8.6.1 for full description). The graph reports the ratio r whereby the numerator is the total sum of points for question i for all of respondents in housing type k, and the denominator is the sum of eligible respondents per question, per housing type. The ratio r allows for relative comparisons within and between each housing type: a block at 100% indicates that all respondents of housing type k received points for that particular question. For example, question X587 has one of the greatest relative importance for farmhouses (indicating whether or not the respondent turns her natural gas heating to summer mode).

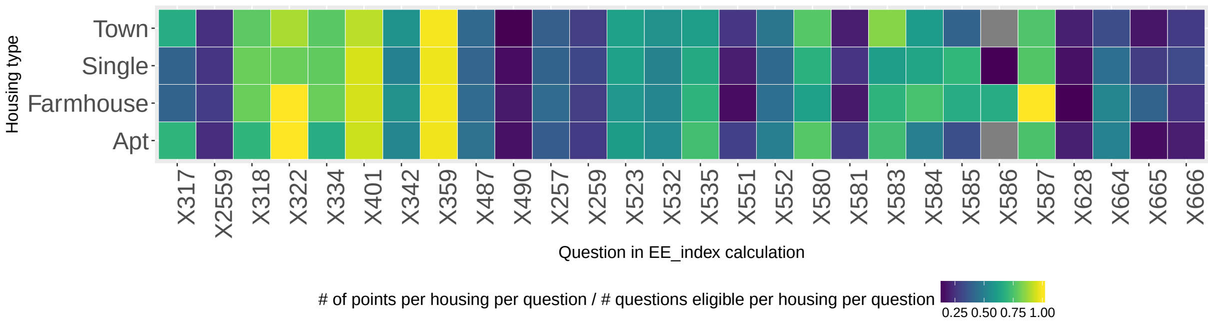

Figure 8.3: Heatmap with ratio r showing relative percentage of EE-index points by housing type.

We noticed that the housing types differ with respect to the EE-index and its composition. Some questions as X359 and X401 are relevant for all housings types with scoring close to 100% (one point awarded if the dishwasher and washing machine, respectively, are filled to over 50% per average use). In contrast, question X334 is relatively less important for apartments (one point awarded if owners of standalone washing machines normally wash at the highest RPM setting). Some questions carry little weight in the final score calculations since they pertain to specific heating technology behaviours such as X666 (a point awarded if the respondent applies a normal step circulation pump in her radiant heating system).

Figure 8.4 shows the correlation between each of the EE-index questions. The purpose of the graph is (i) to assess whether performing a specific energy end-use action is correlated to other actions, and (ii) to identify overall trends in end-use from the survey sample data. An examination of these correlations reveals that there are several clusters of positively correlated variables, indicated by the dark blue colours. For example, one cluster is for

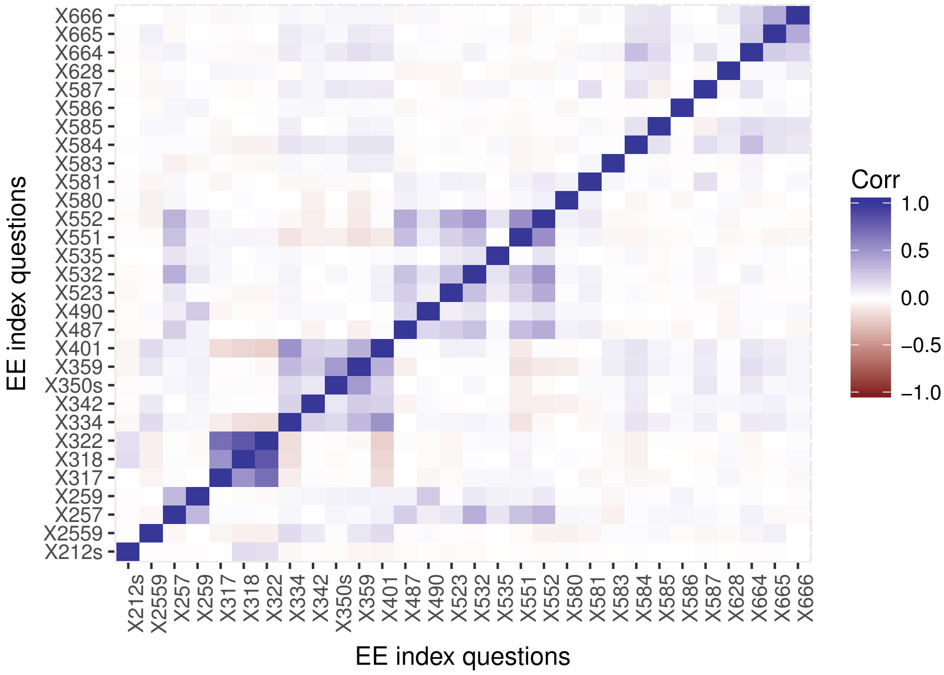

Figure 8.4: Correlation matrix of all EE-index questions

variables X317, X318, and X322, all related to dryer usage. Another positive cluster includes X487, X490, X523, X532, X551, and X552 which pertain to whether or not the respondent removes a specific appliance from the power socket after use. Also, a cluster includes variables X664, X665, and X666, pertaining to behaviour with heating technologies, such as turning your circulation pump to summer mode. The prevalence of these positively correlated clusters suggests that consumers generalise their behaviour by appliance. For example, a consumer who normally washes clothes at a low temperature is more likely to report EE conscious behaviour on remaining washing machine questions. The correlation analysis also shows that there are few negatively correlated variables.

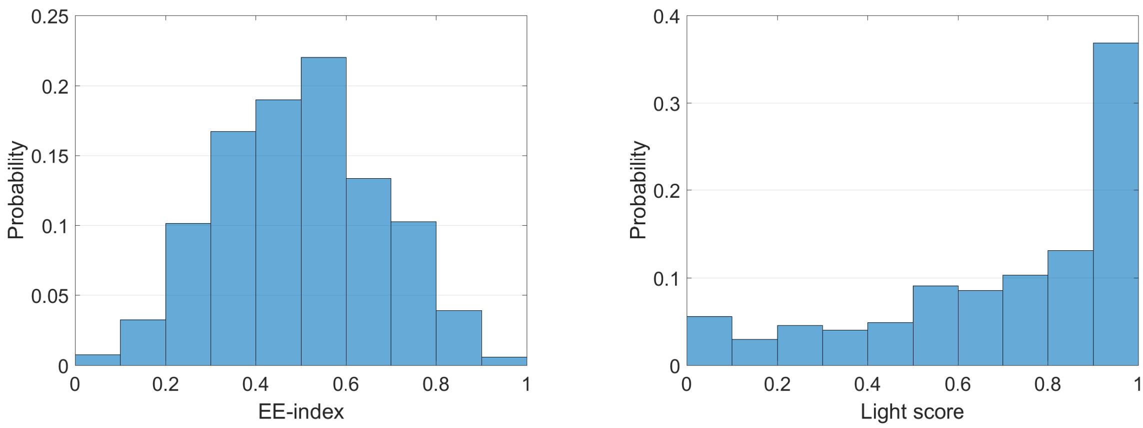

Figure 8.5: Probability distributions for EE-index (left) and light score (right).

The EE-index scores, shown in Figure 8.5 (*left*), present a distribution with a mean of 0.49 and a standard deviation of 0.17 which resembles a normal distribution. In Figure 8.5 (*right*) we also display the distribution of the light score. The score is highly left tail skewed. Moreover, more than 30% of respondents reported having only EE lighting (no incandescent lights), explaining the peak corresponding to an index value in the interval [0.9, 1].

8.4.3 Purchase propensity curves

Propensity curves have been computed to study how the predicted probabilities in EE appliance choice change per variations in the explanatory variables. The curves are evaluated varying one variable at a time, while keeping the others fixed to the following values: income is kept fixed to 400,000 DKK, EE-index, light score and know el. are kept fixed to 0.5, number of inhabitants to 2 and age to class 3.

Figures 8.6 shows the development of the expected probabilities for different levels of income. The trends suggest that the higher the income, and consequently wealth, of the respondent, the higher is the probability that the same respondent will choose more efficient household appliances when investing. The curves are reported for the different type of dwellings to simplify the understanding of the analysis. The differing levels (intercepts) of the curves illustrates the importance of the house type factor: the propensity curves for choosing energy efficient appliances for farmhouses and single houses are on average more than 10% higher than apartments, and up to 15-17% higher for low income levels.

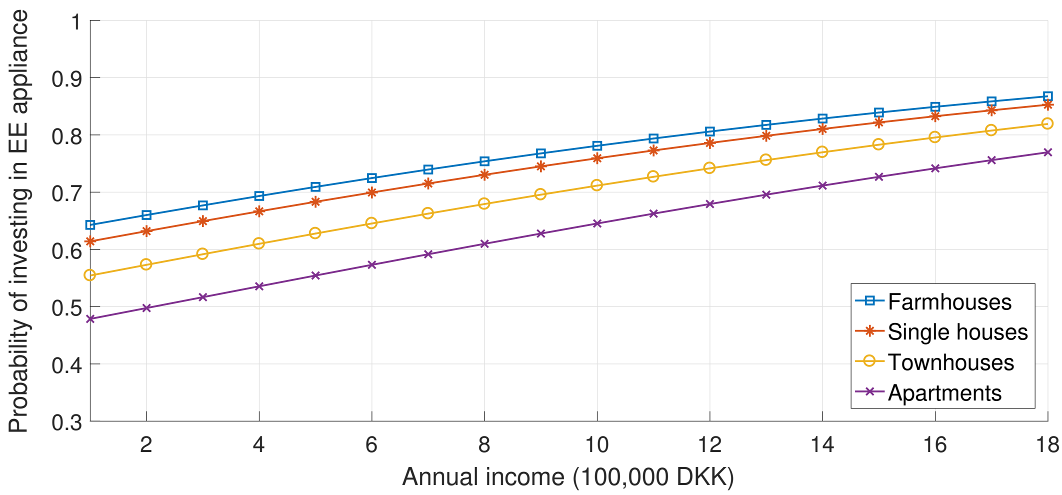

Figure 8.6: Predicted probability of investing in EE appliance by income.

Figure 8.7 and 8.8 report the development of the probabilities for the number of inhabitants and EE-index, respectively. The figures show that a higher number of people living in the dwelling, as well as a higher EE-index, results in a greater predicted propensity for choosing energy efficient appliances. The curve levels for different housing types are consistent with those of Figure 8.6, with farmhouses and single houses being substantially higher than apartments.

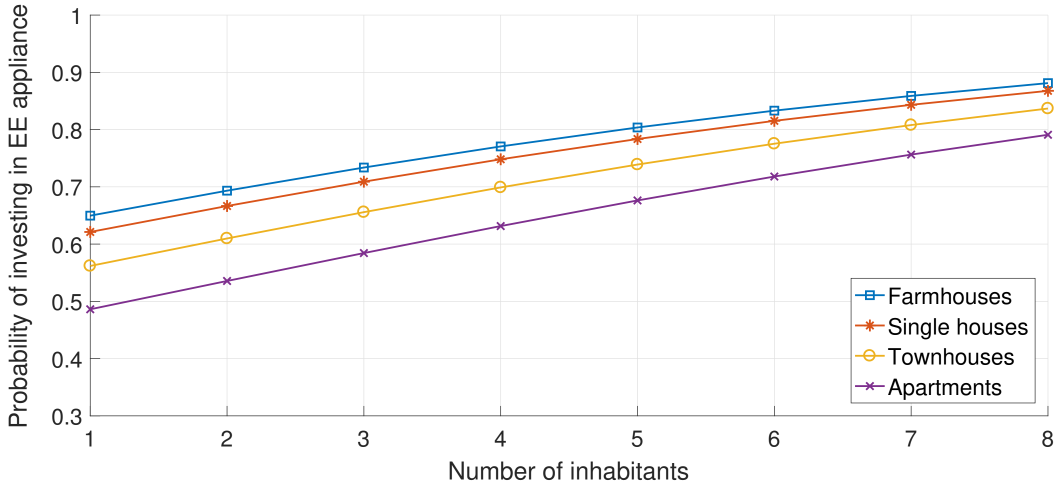

Figure 8.7: Predicted probability of investing in EE appliance by inhabitants.

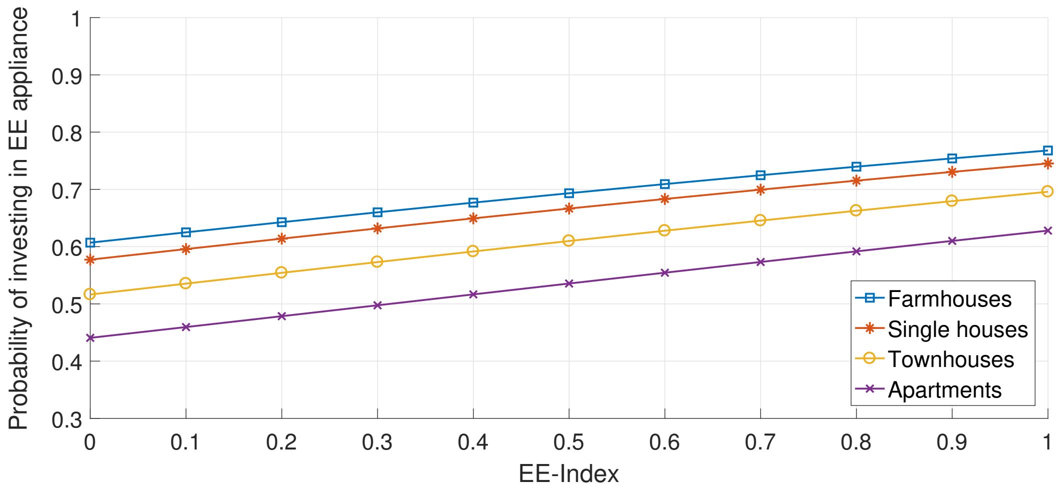

Figure 8.8: Predicted probability of investing in EE appliance by EE-index

Figures 8.9 and 8.10 illustrate respectively, the point-wise estimated probability for varying age and housing type, along with 95% confidence intervals. The results suggest that older respondents have a higher propensity to choose energy efficient appliances, as only the groups 2 through 5 differ significantly from group 1. Likewise, the range of the confidence intervals varies for the different type of dwellings. The apartments and single family houses present larger variation compared to other housing types. Also, the predicted probability is the highest for farmhouses and the lowest for apartments.

The probabilities of choosing EE investments resulting from the model can be perceived as generally high (e.g., the average rates are above 50-60%).

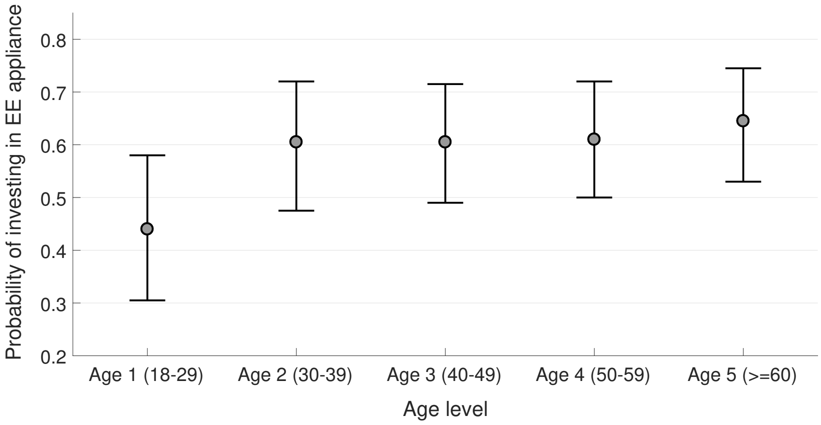

Figure 8.9: Predicted probability of investing in EE appliance by age.

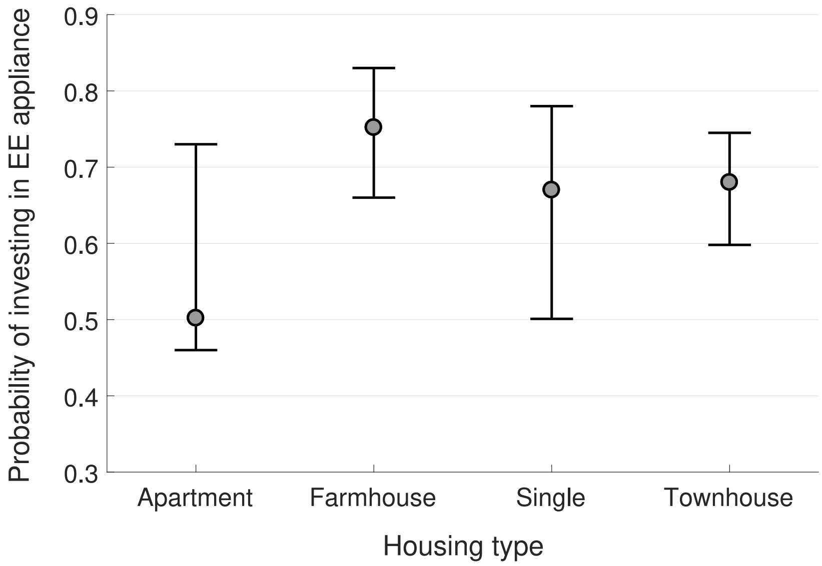

Figure 8.10: Predicted probability of investing in EE appliance by housing type.

This is explained by the original distribution of the reported survey data.

Finally, we assessed the robustness of the model using a marginal effect plot with a bootstrap error, displayed in Figure 8.11 for the different variables. This analysis is employed to assess the sensitivity of the originally computed model estimates to statistical assumptions. The bootstrap method draws 1000 random samples from the original survey data, recalculating model estimates 1000 different times. If the bootstrapped estimates and standard errors deviate substantially from the original values, there is evidence of major violations of statistical assumptions (that is, collinearity or low predicting power resulting from few observations). Like the original coefficients, the marginal effects can be seen as partial derivatives of total joint-probability function. The average of the re-sampled marginal effects is the midpoint, while the tails illustrate the 95% confidence interval. The bootstrapping shows that the income is hardly significant and casts some

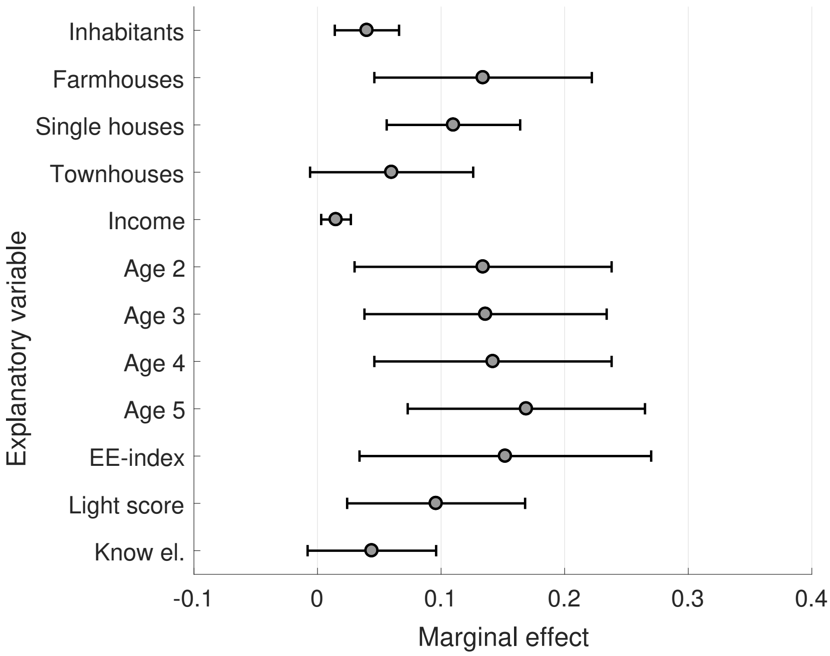

Figure 8.11: Marginal effects with bootstrap errors of the explanatory variables

doubt about the strength of income to predict EE investment choice, compared to the more qualitative EE-index and house setting. Given the results, farmhouses are more likely to choose EE appliances when compared to other house types.

8.4.4 Discussion of the results

The positive correlation between household income and EE appliances adoption concurs with previous studies (Long, 1993; Mills and Schleich, 2010a; Sardianou and Genoudi, 2013; Ameli and Brandt, 2015). However, our results show that income is not one of the strongest predictors to EE appliance purchases when compared to other variables considered. This finding might be specific to Denmark, a country with relatively high income and social welfare; in other countries, household income could possibly reveal to be the strongest predictor. Moreover, given the available data and logistic modelling assumptions, there is no convergence to 100% probability of investment for the highest income classes. In fact, even the highest earning consumers are unpredictable in their choices, and as mentioned, driving factors extend beyond energy efficiency to include cost, quality, brand, and functionality (Gaspar and Antunes, 2011; Baldini and Trivella, 2017).

The building type is one of the strongest predictors of EE appliance choice. In particular, the values of the estimates in Table 8.3 show that farmhouses and single family homes residents are significantly more likely to choose EE investments than apartment residents. The related purchase propensity curves in Figures 8.6-8.8 also highlight the relevance of the household type for this analysis. The curves vary because consumers living in different housing types, on average, own a different number of household appliances and have different levels of wealth and lifestyle. This translates into an energy end-use and attitude towards energy efficiency and environment that can vary substantially among these groups. Apartments, for example, are associated with a lower probability of purchase because they are often rented out, and renters are less sensitive to energy-efficiency investments due to the short length of the stay (see our related discussion in Section 8.5.2). In contrast, farmhouse dwellers typically own the property. Moreover, they are in general more sensitive towards energy-efficiency because farmhouses are, on average, larger than apartments and contain more appliances thus incurring higher expenses for electricity and heating. This leads to a higher purchase propensity as also confirmed by our results. Consistently with this discussion, single houses and townhouses lie somewhere in between as shown in Figures 8.6–8.8. Previous studies focusing on more specific investments (heat pumps, EE windows) agree with such correlation (Mills and Schleich, 2009; Michelsen and Madlener, 2012; Ameli and Brandt, 2015). More technical housing variables such as house size or year of construction appear instead to be insignificant.

Regarding age, respondents younger than 30 years are significantly less likely to invest in EE appliances. Other studies suggest that age, as a predictor, is sensitive to specific technologies: older consumers are more likely to invest in EE light bulbs (Mills and Schleich, 2010a; Mills and Schleich, 2010b), renewable energy technologies as wind mills and solar photovoltaic (Willis et al., 2011), but not heat pumps (Mills and Schleich, 2009; Willis et al., 2011; Michelsen and Madlener, 2012).

On the quantity of inhabitants, the estimates confirm the positive relationship: the odds of investing in EE appliances increase with inhabitants. Several other studies achieved a similar conclusion (Mills and Schleich, 2010b; Mills and Schleich, 2012; Ameli and Brandt, 2015). A larger household inhabitancy results in greater and more intensive energy consumption; reasonably, these households would have a greater incentive to invest in energy savings assuming rational economic behaviour (Bartiaux and Gram-Hanssen, 2005).

The variables light score and know el. result in comparatively strong, positive parameter estimates. Respondents with more EE lighting and those who report knowing their own consumption choose more efficient appliances at the moment of purchase; this suggests that one EE conscious behaviour begets the next.

The EE-index's high significance (and especially large parameter estimate) shows how daily energy conservation actions such as turning off the power socket by night and adapting the heating system to the seasons strongly predict the choice of investing in EE appliances. The positive relationship could be expected since it alludes indirectly to environmental stewardship and energy savings attitudes (and also economic savings). Nevertheless, this paper provides empirical evidence that energy end-use daily actions are correlated with EE investment. Furthermore, the correlation matrix of all the EE-index questions, showing the correlation between the pertinent energy-savings end-uses, has highlighted that particular EE conscious behaviour begets some others. Thus, another practical finding from the EE-index analysis is that respondents generalise their EE behaviour by appliance group.

The correlation between overall high EE-index scores and A+ label investment poses a future research question: do respondents generalise their appliance specific behaviour because they purchased an A+ label (i.e., I buy green therefore I act green), or do respondents seek A+ appliances because they perceive their previous behaviours as green and efficient. One avenue for future research could be to test this relationship through a combination of surveying and direct end-use observations. Observational data is now possible through advanced metering infrastructure and smart appliances. Though there are privacy concerns, observational data would greatly complement a survey sampling which are inherently prone to bias and response errors.

8.5 Conclusions and policy implications

The study aimed to understand which characteristics lead consumers to choose energy efficient appliances at the moment of purchase. Using data from a DEA survey and a statistically sound logistic regression model, socioeconomic, behavioural, and housing characteristics were found to be highly significant when explaining the choice of investments in EE appliances, with housing type and EE-Index being the strongest of these predictors. Particular focus was given to the EE-index, combining all behavioural characteristics pertinent to energy savings, and proving that consumers who performed energy conservation actions regularly were more likely to choose EE appliances.

The outcomes of the study spark suggestions about relevant policy measures. Even though energy efficiency continues to rise among most appliances (Barbieri and Palma, 2017), there are still large groups of the population that for many reasons do not invest in EE appliances. Given the importance of socioeconomic characteristics highlighted by our results, existing labelling directives should be assisted by product designs and promotion targeting citizen with such characteristics, for instance, using subsidised rebates and discounts for consumers who are least likely to undertake the investment. Following the results of this work, we identified three major points that should be addressed while outlining energy saving policies: (i) future development of appliance ownership and population housing, (ii) building ownership versus renting, and (iii) evolution of information campaigns.

8.5.1 Trends of appliance ownership and population housing

As policies are meant to be effective in the long term, it is fundamental to consider the future evolution trends of the appliances. The online tool *El-model Bolig - prognose* (El-model buildings - prognosis, in English; (DEA, 2017b)), developed by DEA, provides forecasts of appliance ownership based on the same 2012 El-model Bolig survey data employed in this analysis, as well as other survey editions (2006, 2008, 2010, 2012 and 2014). The tool allows user-specified inputs and can produce either linear or Gompertz forecasts of appliances' characteristics such as lifetime, sales, quantity, energy use and sales number. Figure 8.12 reports Gompertz forecasts for the sales of five of the major energy intensive household appliances for apartments (*left*) and detached houses (*right*), for the period 2017-2050. The forecasts do not contain labelling information, but provide a projection based on simple historical ownership data.

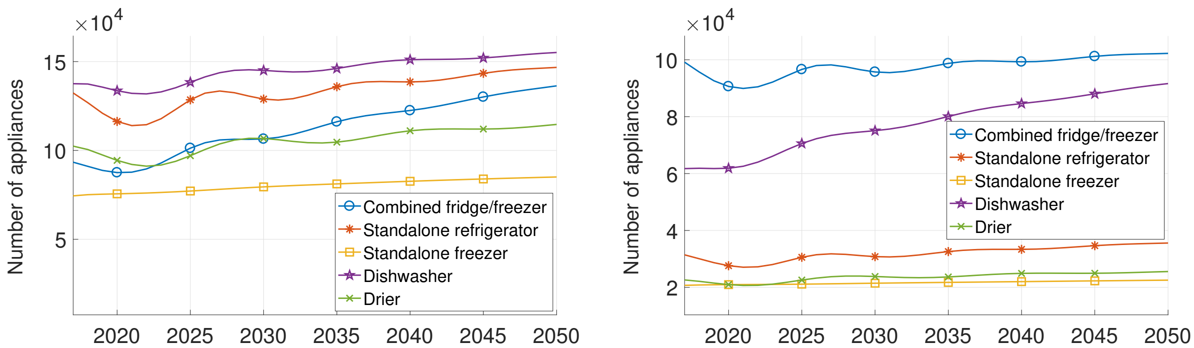

Figure 8.12: Sales forecasts of different appliance categories for apartments (left) and detached houses (right).

The projections for the apartments and detached housing illustrate increasing ownership, suggesting that residents of apartments and detached houses should be targeted for energy efficiency policy related actions. The raising trend of appliances for these housing types is largely due to an underlying increase in Danish urban populations and housing centres (Trading Economics, 2017). Broadening the scale, this trend is consistent with the recent global trends showing that world's population is increasingly urban with more than half living in urban areas (UN, 2014). As urban populations and the number of urban centres continue to grow, rural populations are expected to decrease. These trends entail a shift of housing conditions to more apartments, implying a change in the energy consumption.

Considering these trends and the results of our study, the authors suggest that policy makers emphasise energy efficiency awareness campaigns for urban citizens, for example, by establishing energy audits to sensitise these users on the contribution of each appliance to total household energy consumption and on the benefits that specific energy efficiency investments would bring in the short and long run. With the underlying assumptions that the population does not choose EE appliances partly due to lack of knowledge regarding the benefits of energy saving, subsidies should thus be directed to increase the awareness of energy efficient appliance choice with additional focus on end-use behaviour. This should lead to more conscious energy use and savings, which in turn, as suggested by our findings, is correlated to a higher uptake of energy efficient appliances.

8.5.2 Building ownership versus renters

The status of home ownership should also be considered for targeted information campaigns. Intuitively, renters are less likely to choose EE appliances as it is improbable that such investments will break-even; in other words, renters would not enjoy the long run economic benefits of investing in energy efficiency. In fact, the payback time of investments in EE appliances is usually in the range of 5-25 years (Baldini and Trivella, 2017) while the average stay for a renter is shorter. Also, the lifetime of new appliances generally overruns the stay of renters within the building or even in the city and furthermore, particularly for large appliances such as fridge or dishwasher, the transfer to a new location implies logistic challenges. Empirical analyses have also found that renters were significantly less likely to invest in EE refrigerators, clothes washers, dishwashers, and lighting, for example (Davis, 2012; Krishnamurthy and Kristrom, 2015). Special focus should be on designing subsidies for short term renters, like students, who are usually the least likely to undertake high upfront investment. In addition to living in rented apartments, students have low or no income and are generally younger than 30, all being socioeconomic factors leading to a low adoption rate of EE investments, as indicated by this study. To this end, dwelling owners could benefit from discount rebates when purchasing high-labelled household appliances for renting purposes. This would consequently help short term renters and in particular students who would enjoy EE appliances without bearing high investment cost.

In Denmark, home ownership levels are geographically disparate, being higher in countryside municipalities (50-65%) and lower in the main cities (e.g., only 20% in Copenhagen)

(Kristensen, 2007). Moreover, population forecasts project growth rates of 5-10% across Danish urban centres contrasted to decreasing population rates in rural Western areas (DS, 2017a), supporting our overall recommendation of information campaigns directed especially towards apartment renters.

8.5.3 Evolution of information campaigns

In the past years, Denmark has been active concerning energy efficiency awareness campaigns. Beyond the EU labelling scheme, Ecodesign requirements, and other broad-stroke energy savings targets, there are several Denmark-specific examples pertinent to this study. SparEnergi.dk (DEA, 2017c) represents Denmark government's most advanced platform for helping consumers to make energy savings decisions. Launched in November 2013 by DEA, the website contains a wide range of information on how to interpret the current energy labelling for appliance groups (washing machines, dryers, fridge and freezers, lights), along with minimum labelling recommendations (e.g., A for combined washing machine/dryers, A++ for standalone dryers). The guidelines also focus on the size of the appliances and the monetary and energy savings resulting from the choice of a more efficient appliance compared to another. The platform provides suggestions about consumers' end-use behaviour; for example "fill the machine completely", "turn down the temperature", "short program", "clean filters", "leave room for ventilation" are all listed as means to reduce the energy consumption and achieve savings.

Therefore, the problem seems to be not the information itself, or lack of, but rather dissemination. Policy makers should thus improve the means of communication regarding energy efficiency. With respect to the degree of labelling influence, a recent analysis of EU-member residential energy efficiency policy over the period 1974-2016 casts doubt (Filippini et al., 2014). The study indicated that information campaigns such as labelling did not have a significant effect in promoting energy efficiency improvements over that time period. This result, combined with the findings of our study, suggests that the focus for future policies should extend beyond developing the labelling metric itself, to considering what that metric actually means to the consumer in the moment of purchase.

A personalised app or a feature on a merchant website could convey a simplified trade-off between energy efficiency and cost, such as payback times on a price-premium, for instance, going from a dryer label A to A+++. On the matter, *SparEnergi.dk* has just recently started operating free counselling services through popular social medias (Facebook) and call centres (DEA, 2017a; Viegand Maagøe, 2017), to answer questions related to household energy consumption. Given the recent progress and broad access to technology, information campaigns should extend to technology-based platforms such as mobile apps or social media so that they can reach a broader population. For example, local administrations could create and manage a municipality-based social media page, explaining the main factors contributing to the local household energy consumption and providing recommendations on how to reduce it. After the first sparks, the "neighbours effect" should induces the learning process and the dissemination of knowledge through families and networked communities, leading to a likelihood increase of adoption rates (McMichael and Shipworth, 2013). Also, information and communication technologies can facilitate the transition towards a smarter use of energy by increasing consumer awareness on the impacts related to the number of devices as well as the importance of energy efficiency (Røpke et al., 2010; De Almeida et al., 2011; Zhou and Yang, 2016). For example, smart meters can play an important role by providing visual information about the disaggregated consumption of household appliances or suggesting the consumer to conserve energy during peak hours (Allcott, 2011).

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8.6 Appendix

8.6.1 EE-index composition

Table 5 details the rationale and summary of all the variables included in the EE-index. In particular, the table reports variable name, code, and the total number of respondents that are eligible for scoring, meaning that they own the appliance the question refers to and thus can be scored accordingly.

Table 5: Summary of EE-index questions and scoring rationale

Code	Scoring rationale	Eligible	% eligible
X212	Washing machine temp 29°C or less on average (combi washer-dryer)	52	3%
X2559	Washes clothes at 70°C less 1 time/wk	1442	84%
X257	Remove PC from power socket	1057	62%
X259	PC set to automatically shut down	1057	62%
X317	Dryer used at highest RPM on average	52	3%
X318	Air drys clothes in summer more than using electric dryer (combi washer-dryer)	52	3%
X322	Dryer filled over 50% on average	52	3%
X334	Washing machine used at highest RPM	1442	84%
X342	Air drys clothes in summer more than using electric dryer (standalone dryer)	940	55%
X350	Washing machine temp 29řC or less on average(standalone dryer)	1299	76%
X359	Dishwasher filled over 50% on average	1298	76%
X401	Washing machine filled over 50% on average (standalone washer)	1442	84%
X487	Removes TV from power socket after use	1689	98%
X489	TV set to automatically shut down	1689	98%
X523	Removes laptop from power socket after use	1448	84%
X532	Removes printer from power socket after use	1539	90%
X535	Removes scanner from power socket after use	173	10%
X551	Removes router from power socket after use	1716	100%
X552	Removes other PC/misc electric equipment from power socket after use	1716	100%
X580	Temperature setpoint at 21°C or less	1687	98%
X581	Temperature setpoint regulated night/day	1649	96%
X583	Turns off electric floor heating in summer	175	10%
X584	Turns off radiant floor heating in summer	345	20%
X585	Turns oilfloor to summer-mode	135	8%
X586	Turns oil/wood heating to summer-mode	11	1%
X587	Turns natural gas heating to summer-mode	192	11%
X628	Uses air-to-air heat pump for cooling	72	4%
X664	Changes circulation pump's step in summer	760	44%
X665	Regulates (up/down) circulation pump	522	30%
X666	Has a normal step circulation pump	256	15%

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Chapter 9

Cost-effectiveness of building energy conservation measures in a Danish district heating area

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Abstract: The paper presents an analysis on cost-effectiveness of energy conservation measures (ECMs) for a building sample in the district heat area of Aarhus (Denmark), considering specifics about measures (e.g. type) and buildings (e.g. energy performance certificates, EPC). Using a building-physics based building stock energy model, cost curves for gross and net potentials were calculated. The study evaluates cost-effectiveness based on net present value of cash flows comparing investments with the cost of heat consumption. In other scenarios, we analyse the effect of different district heating tariffs structures, in relation to the uptake of energy savings. We found cost-effective gross energy-saving potentials summing to 50.4 GWh and related net potentials of 8.4 GWh. Both approaches show maximum marginal cost at 1.7 €/kWh, with the cost-effectiveness of ECMs varying considerably among building groups. The results show relevant sensitivity to variations in discount rates. When all cost components are made variable, we observe that attractive EMCs in buildings with high EPCs are linked to the subscription payment while for buildings with low EPCs, most investments are related to the consumption and capacity components. We discuss implications of the tariff structure at energy system level, highlighting a synergistic effect between energy savings and district heating supply. Policy makers should thus support renovation costs for particular measures in building categories, encouraging end-users to invest and contribute to lower energy needs, paving the way for a more sustainable future.

Keywords: Heat savings · Cost curves · Danish building stock · District heating · Energy conservation measures · Cost-effectiveness · Energy performance certificate data

9.1 Introduction

In the framework of mapping paths towards a more sustainable future, energy efficiency and renewable energy based technologies can provide cost-effective ways of decarbonising the European energy system. Buildings play an important role in the European strategy to reduce greenhouse gas emissions, as they account for approximately 40% of the total energy consumption in the EU (European Commission, 2018).

9.1.1 Energy efficiency from a demand side perspective

The poor energy efficiency of the (aging) European building stock, make buildings eligible to energy efficiency upgrades. The Energy Efficiency Directive (EED) (European Commision, 2012) as well as the Energy Performance of Buildings Directive (EPBD) (European Commision, 2010) require member states to improve the energy efficiency of their building stocks, as long as it is cost-effective.

In the residential sector, the individual consumer can decide to perform investments in energy conservation measure (ECMs), hence we evaluate the cost-effectiveness from a private end-user perspective. As these measure reduces the heat demand of the building, the cost-effectiveness of investment can be evaluated by comparing, over the lifetime of the investment, the cost of the measure directly with the cost of heat.

9.1.2 Energy efficiency from a supply-side perspective

In Denmark, approximately 60% of all buildings are connected to a district heating (DH) network. An effective way of reducing transmission losses in DH pipes is by lowering the supply temperature, and this can happen as far as the consumers energy demand can be met. In this regard, improving energy efficiency in buildings (i.e. reducing energy needs) can support this transition, along with other multiple benefits: (i) avoiding heat production, (ii) lowering the supply temperature needs and (iii) saving additional network capacity. In addition to the listed positive effects, Danish energy supply companies are also required to realise cost-effective end-use energy savings (Forsygnings og Klimaministeriet, 2015; Forsygnings og Klimaministeriet, 2018). Realising this potential requires a detailed assessment of the cost-effectiveness of ECMs in the building stock.

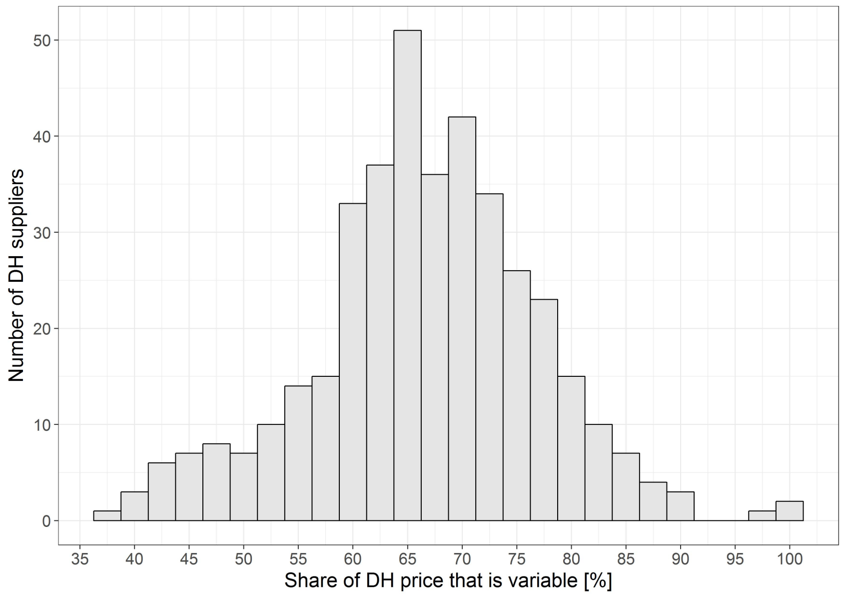

Figure 9.1: Distribution shares of DH variable heat cost component (Danish Utility Regulator, 2018)

9.1.2.1 District heating tariff structure in Denmark

For a private Danish consumer, district heating prices normally consists of a fixed- and a variable part. According to heat legislation from the Danish Utility Regulator, the cost of heat generation from district heating networks is available to the public and is updated regularly on yearly bases (Danish Utility Regulator, 2018). The price of heat differs from one district heating area to another, in relation to the local conditions and generation costs. As investments in energy conservation measures reduce the need of heat for the building, the cost of investing in an ECM competes directly with the variable part of the cost of heat. To have an overview on the difference in costs between district heating areas in Denmark, Figure 9.1 provides the share of the variable part of district heating prices, showing that the share of DH variable heat cost component differs considerably among area. As a consequence, the type- and number of cost-effective ECMs can be expected to vary significantly among DH areas.

When aiming at reducing energy consumption in the built environment, the cost-effectiveness of ECMs could be enhanced by increasing the variable share of the DH price (i.e. making more parts of the price variable to reflect better the cost of energy production). In this regard, private consumers connected to district heating are also exposed to other costs, considering e.g. capacity or connection. Although being fixed payments on yearly bases, capacity payments can be subject to reductions according to specific consumption characteristics of the building, hence offering a potential for improving the cost-effectiveness of ECMs.

9.1.3 Aim and objectives

In this study we investigate on the cost-effectiveness of investing in energy conservation measures from a private end-user perspective, based on the analysis of a sample of buildings connected to the district heating area of Aarhus, in Denmark.

The study was motivated by the following research questions:

- What is the energy saving potential, related with cost-effective energy-conservation measures, for the sample residential building stock?
- How is the cost-effectiveness of energy conservation measures related with the energy efficiency of buildings?
- What is the difference in cost-effective investments, for gross and net energy saving potentials?
- What is the value of the attractive measures, in terms of economic and energy savings?
- And finally, is there an effect on exposing the private consumer to different heat tariffs, in relation to a potential uptake of energy savings measures?

In order to estimate the cost-effectiveness of an energy conservation measure (ECM), cost curves were used for relating the effect of an ECM with the corresponding cost of employing it. Energy savings, in terms of the heat demand before and after implementation of an ECM, were calculated for each building component individually using a model developed by (Brøgger and Wittchen, 2017). This was done on the basis of the building-physical characteristics of each component, as recorded in the Danish energy performance certificate (EPC) database, to provide an estimate of the *gross* energy saving potential.

However, technical energy saving potentials in buildings can be often overestimated because implicit factors, related to e.g. energy consumption, rebound and pre-bound behaviour by the inhabitants or building thermal characteristics after an energy upgrade, are disregarded (Haas et al., 1998; Hens et al., 2010). To deal with this limitation and to get an evaluation of the realisable energy savings-that is, estimate how much an energy-conservation measure is likely to actually reduce the heat consumption-we rely on the work performed by Brøgger et al. (2018) to compute *net* energy savings potentials.

On the bases of these estimates, the cost-effectiveness of ECMs was evaluated in relation with the energy-efficiency of each building (in terms of EPC[1]). To this end, we use as proxy a positive net present value of cash flow, comparing the marginal investment costs with the resulting savings. Furthermore, we explore the effect of variations in district heating tariffs on the overall uptake of energy saving measures.

The study contributes to the field by developing a methodology resulting in practical findings that can be useful for end-users, policy makers and institutions. By providing empirical results on cost-effectiveness of heat saving measures in residential buildings, the paper broadens the knowledge on attractive residential energy savings and on the influence of heat-tariffs in cost-effective energy saving investments.

The remainder of the paper is organised as follows. In Section 9.2 we review the literature on estimation of energy savings potentials and methods to evaluate the cost-effectiveness of energy conservation measures. In Section 9.4 we describe the data and in Section 9.3 we introduce the methodology adopted. In Section 9.5 we describe the results, which we further discuss in Section 9.6. We conclude in Section 9.7 summarising on the study and reporting policy suggestions based on our findings.

[1]The energy performance certificate evaluates the energy efficiency of a building, rated on a scale from A (most efficient) to G (least efficient).

9.2 Literature review

Studies suggest that energy efficiency should be prioritised as, lowering the energy needs while still maintaining the same services, it allows to decouple economic growth from rising energy consumption and greenhouse gas emissions (Baldini and Klinge Jacobsen, 2016). Energy efficiency is thus a "low hanging fruit" ready to be harvested (Galvin and Sunikka-Blank, 2013). Nonetheless the reality highlights that, despite the relevant potential available, the theoretical (or gross) savings that could be achieved are not realised. Worldwide researchers acknowledge this discrepancy as the Energy Efficiency Gap (EEG) showing, through empirical and theoretical examples, that the EEG is hard to overcome (Hirst and Brown, 1990; Gillingham et al., 2009; Gillingham and Palmer, 2014). Among the reasons identified there are distorted consumer behaviour, lack of awareness on energy efficiency or non economical attractiveness (Huebner et al., 2016; Scott et al., 2014; Galvin and Sunikka-Blank, 2013). In order to identify barriers that hinder the development of energy efficiency, four key questions are the focus of the research debate:

1. How to calculate the gross potentials for energy savings?
2. In relation to energy savings investments, how to deal with the post-renovation demand related effects?
3. What are the methods to assess cost-effective investments?
4. How to assess attractive investments, from a socio-economic and private perspective?

In line with the target of the paper, we elaborate on these questions focusing on heat savings measures in the residential sector.

9.2.1 Energy savings in the residential building stock

In Europe, the residential building stock holds a large untapped energy saving potential related to energy-upgrading of the building envelope (Nemry et al., 2010). Bottom-up building physics-based models are widely used for assessing the energy saving potential given an energy-upgrade of building components, e.g. roofs or external walls (Kragh and Wittchen, 2014). These models are mostly based on a description of the thermal characteristics of the considered building stock, for which reason they are often referred to as *engineering methods* (Swan and Ugursal, 2009) or *first-principle methods*.

Building archetypes (i.e. synthetic/average buildings) are generally used for assessing the energy saving potential of a building stock (Wittchen et al., 2017; TABULA Project Team, 2012). However, the use of archetypes is associated with loss of diversity, i.e. archetype heterogeneity (Booth et al., 2012) which could have an impact on the cost-effectiveness of an energy conservation measure, e.g. if the actual energy-performance of a particular building was different from the archetype. With this in mind, we calculate gross energy saving potential anew for a number of energy conservation measures, based on the characteristics of existing buildings at the individual component level (e.g. area, orientation of the house, etc..).

9.2.2 Gross and net energy saving potentials

Building-physics based methods provide an estimate of the *gross* energy saving potential; i.e. assuming that boundary conditions in terms of indoor temperatures, air change rates, etc. are not affected by energy upgrading a building. However, several studies have identified a *performance gap*, i.e. a discrepancy between the energy demand calculated in a building-physics based model and actual household energy demand. In particular, consumers living in energy-efficient houses use more energy in relation to the energy performance of the building, compared to residents living in energy-inefficient houses (Majcen et al., 2013). This suggests that energy savings achieved in practice, due to energy conservation measures, can be lower than those calculated in engineering conservation studies, causing an overestimation of the *net* energy savings (Majcen et al., 2016). With this in mind, in the paper we develop and evaluate the cost-effectiveness of both gross (technical) and net (realisable) heat saving potentials. For the net savings, reflecting a more realistic evaluation of the savings available, we refer to results achieved by Brøgger et al. (2018), based on a multiple linear regression model.

9.2.3 Cost-effectiveness of energy conservation measures

Once the potentials are determined, researchers focus on establishing which are the cost-effective investments, by comparing the benefits of an investment with the related costs. The most traditional methodology is based on Discounted Cash Flows, using a positive net present value (NPV) as a proxy for attractive investments. Different case studies in the literature employed a similar methodology, while focusing on energy savings measures for the residential sector. For instance, Amstalden et al. (2007) use it to analyse the profitability of energy-efficient retrofit investments in the Swiss residential building sector from the house owners perspective; Gaterell and McEvoy (2005) use it to investigates the impact of environmental externalities and social costs on the performance of a range of insulation measures applied to an existing residential dwelling; and Tommerup and Svendsen (2006) use it to look into cost-effective technical energy saving possibilities in the Danish building stock.

Furthermore, in the framework of energy systems optimisation models, marginal cost curves are often employed to provide an easier understanding of the economically available measures, comparing savings and supply opportunities from an energy system perspective to find the most cost-optimal trade-off between demand and supply. As an example, Zvingilaite (2013) employ cost curves while modelling energy savings in the Danish building sector internalising health related externalities in a heat and power system optimisation model and Zvingilaite and Balyk (2014) focus on heat savings in buildings in a 100% renewable heat and power system in Denmark with different shares of district heating. Zvingilaite and Klinge Jacobsen (2015) perform similar work while modelling residential investment behaviour with local health costs, while Münster et al. (2012) estimate the potential for district heating expansion in the future Danish energy system, given individual heating or heat savings measures available.

Due to the broad perspective assumed for energy systems analyses, most of the studies often report an approximation of typical household residential buildings, proposing measures with average characteristics generalising saving potentials on the basis of building archetypes, which may cause the results to be artificially homogeneous.

With this in mind, we consider a method based on net present value of investments, investigating on cost-effective measures under different conditions. We perform such analysis on the bases of a database considering (i) high-level details on building components and related savings along with (ii) calculated heat consumption of the building under analysis.

9.2.4 Cost-effectiveness perspectives

The cost-effectiveness of investments can be assessed from either a socio-economic or from a private-economic perspective. The socio-economic approach is common in energy systems analysis, where attractive saving investments are evaluated in comparison with the supply options available at system scale, aiming at cost-effective measures that contributes to the main objective (being this an energy system with lower overall CO_2 emissions or simply the least-cost supply energy system configuration to satisfy the energy demand).

On the other hand, a private-economic perspective is often used for analysing investments from the consumer side. Investments in energy savings in residential buildings are made by the end-user; socioeconomic and behavioural factors, external regulations and local policies can influence the decision process. Compared with the socio-economic perspective, the private consumer is exposed to different price levels (e.g. consumption and capacity charges) in regard to the heat-cost. Furthermore, the final heat price for the consumer includes charges, considering e.g. network capacity or grid connection, which are usually added on top of the heat-production cost. These factors increase the heat-price, which, consequently, can unlock a broader range of cost-effective energy savings measures (i.e. the higher the heat-cost, the more attractive the heat savings measures). Other studies, focusing on energy savings for the households sector, have already suggested a greater attractiveness of investments for the private consumer compared to a socio-economic approach (Baldini and Trivella, 2017).

To this end, in this paper, we investigated on the cost-effectiveness of heat savings measures from an end-user perspective, exploring the effect of making various heat-cost components variable, to foster a larger uptake of heat savings.

9.3 Method

9.3.1 Evaluating cost-effective levels of energy conservation measures

In the present study, an individual building stock energy model was employed. This entails that energy demands were calculated for each building individually, based on the physical characteristics of each building component as described by Brøgger and Wittchen (2017). Furthermore, energy consumption was studied at a whole building level (e.g. a block of flats or a detached single-family house), since potential energy savings are often estimated at this level, rather than on a single unit (e.g. an apartment) level. The building-physics based model was based on the monthly mean calculation method specified in EN ISO (2008), meaning that consumption profiles were not considered.

In order to identify cost-optimal levels of each energy conservation measure, cost curves were used. These were based on the heat demands calculated in a building-physics based model developed by Brøgger and Wittchen (2017) to get the gross energy saving potential of each ECM. By calculating the energy saving potential of each component individual, it was possible to evaluate several levels (e.g. insulation thicknesses), in combination with the associated costs, simultaneously; i.e. the cost curves were used for illustrating the cost of reducing the energy demand by a given amount, in €/kWh for each ECM. It should be noted that all heat-demands as well as potential energy savings were calculated anew for this study specifically.

Four building envelope components were considered for energy upgrading: roofs, floors, external walls and windows. In addition, the possibility of installing a mechanical ventilation system with heat recovery was considered. In the present study, only exterior re-insulation was considered as interior re-insulation requires a case specific assessment of the moisture conditions in order to avoid problems with mould growth.

In terms of external wall related energy saving measures, three possibilities generally exist: exterior re-insulation, interior re-insulation and cavity wall insulation (with cavity wall insulation only being applicable in hollow walls). In the present paper, only exterior re-insulation of massive external walls and cavity wall insulation (i.e. hollow external walls) is considered, because the price of insulating the two are substantially different. The possibility of insulating a cavity wall externally was also considered, in order to include more ambitious measures.

9.3.1.1 Marginal cost curves

In the present paper, a part for windows measures, we employ marginal costs of ECM. Hence, wages, price of scaffolding, etc. were not included in the prices, which thus only include the material costs. As an example, Figure 9.2 illustrates heating cost curves for three eligible ECMs for external walls. Evidently, cavity walls possess a considerably more cost-effective energy saving potential, even though this potential is not as large as the one related to exterior re-insulation.

All roofs were assumed to be identical, i.e. no distinction was made between flat roofs and gable roof (i.e. roofs with a slope) because this information was not available. This have an impact on the maximum possible insulation thickness, which was thus not considered. However, as this only applies to the most ambitious measures (i.e. the largest insulation thicknesses), it should not affect the results considerably.

As with roofs, no distinction was made between different types of floors (e.g. crawl-spaces, cellars, etc.), in terms of costs assumed. As only marginal costs were considered, this should not affect the results considerably. Two types of windows were considered in this study: 2-pane (energy class B) and 3-pane (energy class A) windows. For the analysis, we considered the cost of replacing a window as the price of the window itself, as a component. Hence, windows were an expensive component material-wise, e.g. in comparison with

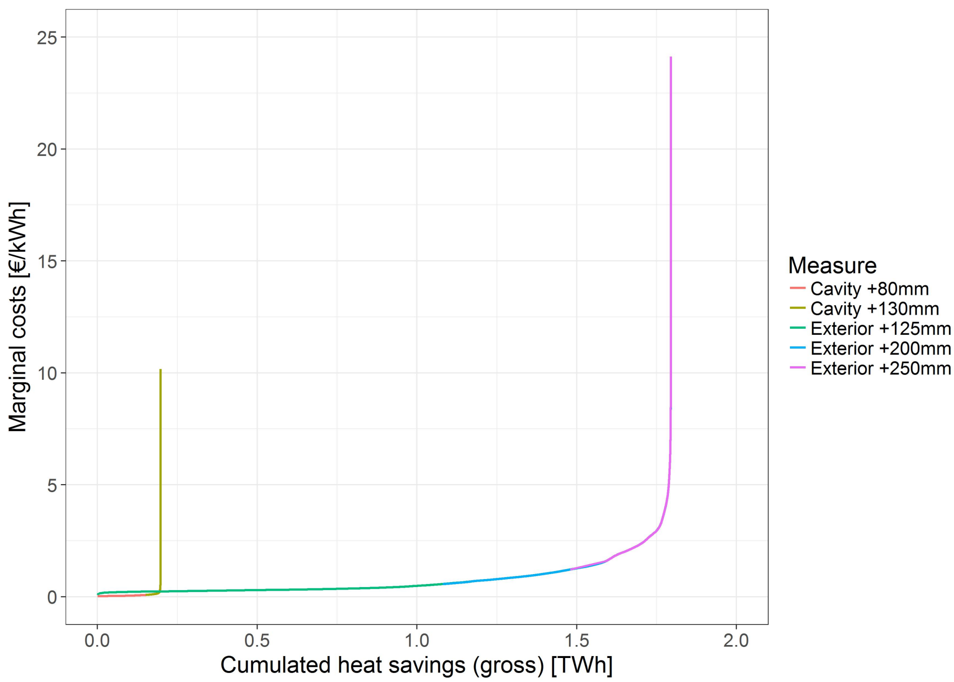

Figure 9.2: Example of heating cost curves - Ext. walls

insulation. As a consequence, replacement of windows may not be considered as cost-effective as energy-upgrading other components. The price of the least energy-efficient window could have been assumed to be zero, if these were to be replace by the end of their service lift. However, as all other ECMs could be employed without replacing them (e.g. an external wall could be re-insulated without replacing it), this was not assumed in the case of windows.

Lastly, mechanical ventilation was considered an ECM because of the the possibility of heat recovery. The price of installing a mechanical ventilation system was assumed to be fixed per unit area. Hence, no distinction was made between different building types, nor sizes. However, it could be that installation of a mechanical ventilation system would depend on the size and geometry of the building (e.g. the number of floors).

It should be noted that, as architectural concerns were not considered, some ECMs may not be implemented, even if they turn out to be cost-effective, e.g. because a facade is worthy of preservation. All eligible energy conservation measures are listed in Table 9.3.

9.3.1.2 Correcting for post-renovation demand related effects

It is commonly known that energy saving measures hardly ever reach their full potential (Haas et al., 1998; Hens et al., 2010), meaning that the full technical potential for energy savings is not likely to be realised when a building is energy upgraded. In a building-physical context, this can be related with the fact that energy savings are exchanged for a better indoor climate, e.g. be it keeping a higher indoor temperature, better air quality due to larger air change rates or the like. Hence, the net energy saving potential was estimated by adjusting the gross potential energy savings, by means of a multiple linear regression model, considering multiple factors, such as energy-performance of each buildings or building type, as described by Brøgger et al. (2018).

9.3.2 Evaluating the cost-effectiveness of an ECM

The cost-effectiveness of an energy conservation measure was evaluated by means of discounted cash flows, comparing the cost of the measures with the related (economic) savings, in line with other studies (Amstalden et al., 2007; Tommerup and Svendsen, 2006; Gaterell and McEvoy, 2005; Jakob, 2006).

In this study, we assume marginal cost of investment, that is the additional cost of investing in a more energy efficient measures, compared to the least performing measure available for renovation. The assumption relates to the long-term perspective on investments, and assumes that renovation in the building will occur at some point on time. Consequently, we disregard timing and reasons that would move an end-user to invest.

The extra investment cost of the more efficient measure c_i is compared with the expected economic saving resulting from the avoided consumption throughout the lifetime of the measure. The Net Present Value (NPV) of investing in an ECM (i) was evaluated according to Eq.(9.1):

$$NPV1_i = -c_i + \left[\sum_{y=1}^{L_i} \frac{\alpha_y}{(1+\rho)^{y-1}} \; (p^c \, \xi_i^{max}) \right] \tag{9.1}$$

where p^c denotes the price related with heat consumption in [€/MWh]. An investment was deemed cost-effective in case of positive net present value of cash flows. Eq.(9.1) represents the trade-off between investment cost and cumulative annual saving. The expression inside brackets is the economic saving for the current year, calculated by multiplying the consumer price with the consumption reduction achieved for every measure ξ_i^{max} [2]. This expression is then summed over a number of years y corresponding to the lifetime of the appliance L_i, discounted according to a discount rate ρ and multiplied by a factor α_y indicating the expected change (increase or decrease) of energy prices for year y.

[2] Based on this method, we assume constant savings throughout the lifetime. Hence we disregard deterioration of the performances in the long term and changes in expected occupancy and use of the building, which can impact the level of savings (Eleftheriadis and Hamdy, 2018).

9.3.2.1 Effects of changing the tariff structure

According to the current heat tariff structure, the cost of an ECM only competes with the variable part of the DH price (consumption). Although straightforward, the reasoning locks out a wide range of energy saving potentials, which could be attractive (cost-effective) if more heat-cost component were variable. For instance, if the heat-tariff was structured in such a way to allow a reduction of the capacity payment, proportionally to the savings achieved by investing in a particular measure, more heat saving measures would result cost-effective. This can be seen as an extension of the existing possibility of obtaining a discount on the capacity fee given compliance with the 2015 building regulation (BR15); further details are provided in the upcoming sections.

The analysis could implicitly assume that the current tariff elements do not reflect real costs. Hence, allowing savings interventions to be rewarded through cost reductions, could compensate for such discrepancy. Also, the method can be seen as a mean to investigate how (and if) savings could contribute to reduce long-term capacity costs.

We thus consider an adjusted version of Eq.(9.1), where we include the economic savings related with the reduced yearly capacity payment component, proportionally to the energy saved by measure i:

$$NPV2_i = -c_i + \left[\sum_{y=1}^{L_i} \frac{\alpha_y}{(1+\rho)^{y-1}} \left(p^c \, \xi_i^{max} + \frac{\xi_i^{max}}{q} p^{pg} \, \lambda \right) \right]. \tag{9.2}$$

In Eq.(9.2), q represents the heat consumption from the building in which the measures can be implemented, p^{pg} the capacity price in [€/m^2] and λ the gross heated floor area of the individual building. As through Eq.(9.2) the private consumer can gain economic benefits by reducing both consumption and capacity heat cost-components, we expect an increase in the number of investments in heat savings measures.

Last, we consider an extreme case in which all heat-cost components are variable. Consequently, we extend Eq.(9.2) according to:

$$NPV3_i = -c_i + \left[\sum_{y=1}^{L_i} \frac{\alpha_y}{(1+\rho)^{y-1}} \left(p^c \, \xi_i^{max} + \frac{\xi_i^{max}}{q} p^{pg} \, \lambda + p^s \right) \right] \tag{9.3}$$

with p^s being the yearly subscription price in [€]. In practical terms, this means that by investing in heat savings measures, the building could disconnect from the district heat network. The case implies two fundamental assumptions: (i) disconnecting from district heat supply is a valid possibility (nowadays, users are not allowed to disconnect from the district heating network that supplies heat to the building); and (ii) there is an alternative heat source which, after the implementation of ECMs, can supply the remaining heat demand at lower costs than district heating costs. Although the listed assumptions might not be currently realistic, pertinent actors in relevant institutions are discussing the possibility of re-thinking such policy for a future where district heating prices might increase (e.g. because of higher fuel costs) and building energy demand will be consistently reduced.

Throughout the results, we refer to Eq.(9.1) for the *Base case*, Eq.(9.2) for the *Capacity reduction case (Cap.reduction)* and Eq.(9.3) for the *Total reduction case (Tot.reduction)*, with input data according to Table 9.5.

9.4 Data description

According to the methodology presented, we now report a description of the data. We first present the technical data about the building stock, and then we introduce the inputs for the case study.

9.4.1 Base data characteristics

The main source of data for the analysis is the Danish energy performance certificate (EPC) database. This includes building-physical characteristics (e.g. areas and U-values) of each component in each building (i.e. walls, roofs,..), as well as other building characteristics (e.g. year of of construction, heat supply, building type and EPC). Moreover, the geographical location and the annual heat consumption from the past three to five years, registered by utility companies, were available for all buildings.

The sample available included 12 589 residential buildings connected to the district heating network in Aarhus, corresponding to a coverage of 18.6%[3]. To verify that the sample is representative, in Table 9.1 we compared the distribution of the construction year in the sample with that of the city of Aarhus. The year of construction, as well as the specific grouping, was used as a proxy for the energy efficiency of the buildings, as suggested by Kragh and Wittchen (2014). The sample distribution is displayed in Table 9.1 and is deemed fairly representative. Some differences compared to the national statistics hold, but overall are acceptable.

[3]Coverage in regard to the building stock connected to the same district heating network.

Table 9.1: Share of buildings by year of construction: survey sample and city of Aarhus

Year of construction	< 1890	1890 – 1929	1930 – 1949	1950 – 1959	1960 – 1972	1973 – 1978	1979 – 1998	1999 – 2006	> 2006
Sample [%]	2.9	15.0	11.5	8.9	20.0	9.2	18.3	5.9	8.3
Aarhus [%]	2.5	11.9	9.6	8.4	21.4	12.0	20.4	7.3	6.4

Having access to the physical characteristics of each building component in the sample, specific energy conservation measures could be analysed, hence entailing that the actual buildings, and not just synthetic (i.e. archetype), were considered. This included an assessment of the cost-effectiveness of energy-upgrading each component individually in terms of potential energy savings and related costs.

Table 9.2 lists the components that were considered for energy-upgrading according to the respective building's EPC[4].

Table 9.2: Summary table for dataset under investigation.

	EPC									Total
	A2020	A2015	A2010	B	C	D	E	F	G	(K Units)
N°of buildings	12	71	373	1505	3482	3886	2011	867	382	12.6
N°of measures										
External Walls	72	426	2238	9030	21000	23840	12678	5616	2636	77.5
Floors	36	213	1116	4512	10443	11661	6033	2601	1146	37.8
Roofs	48	284	1492	6020	13928	15548	8044	3468	1528	50.4
Ventilation	11	70	295	1244	2991	3395	1686	707	296	10.7
Windows	139	650	3636	15474	39124	50895	29064	13610	6022	158.6
Share of total measures by EPC	0.1%	0.5%	2.6%	10.8%	26.1%	31.4%	17.2%	7.8%	3.5%	100%

In line with other studies, we assumed a lifetime of 60 years for external walls, 60 years for floors, 40 years for roofs, 40 years for ventilation systems and 30 years for windows (Trafik-, Bygge- og Boligstyrelsen, 2018; Wittchen et al., 2017). Furthermore, Figure 9.3 illustrates the gross heat demand of the sample, calculated according to Brøgger et al. (2018). In total, the gross heat demand for the considered sample building stock was 541.1 GWh and the corresponding net heat demand was 437.8 GWh.

[4]Clarification note: the values represent energy-upgrading opportunities elements (measures) which could be replaced in the buildings. For instance, considering that there is a total of 12.6 K buildings, and 77.5 K external walls measures, on average there are 12.6/77.5 = 6 external wall renovation opportunities for every building. Nevertheless, differences apply for building categories according to EPC labels.

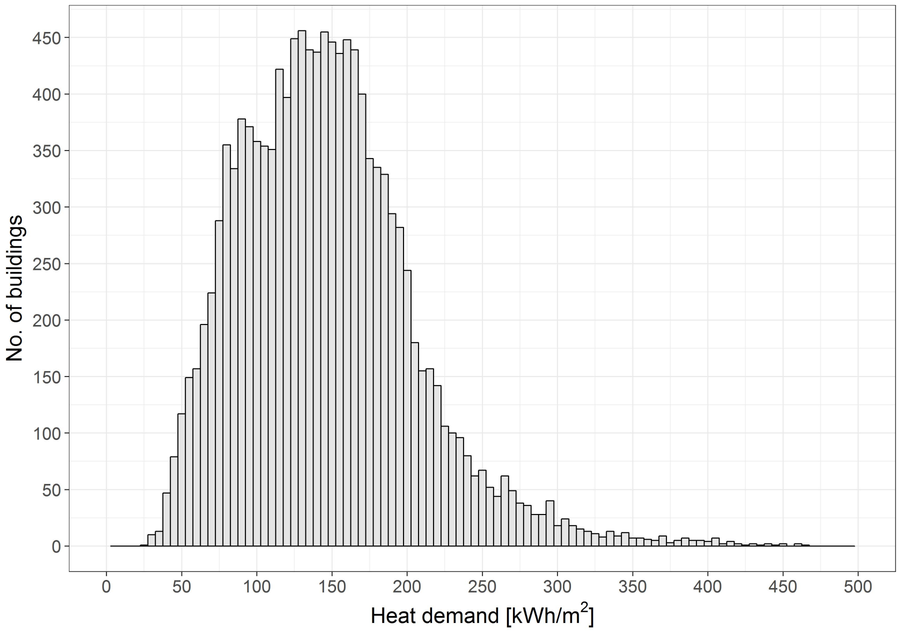

Figure 9.3: Calculated gross heat demand of the considered building stock (sample)

9.4.2 Eligible energy conservation measures

As insulation batches normally come in predefined thicknesses, only standard thicknesses that were available to the market were considered; hence the step-wise increase in insulation thicknesses.

Table 9.3 lists the eligible ECMs and the associated costs of adopting a particular level of a measure, with price values according to Molio.dk (2018). The 'Level' column specifies the properties of a given ECM, e.g. the insulation thickness to be added to the existing construction (or the energy class, for windows). The λ value specifies the assumed thermal conductance of the insulation material. Likewise, the U-value denotes the thermal properties of the windows and η is the efficiency of the heat recovery in the mechanical ventilation system.

The 'Costs' column specifies the marginal costs of adopting the corresponding level of an ECM, i.e. the additional costs (+ 7.1 €$/m^2$), compared with the previous level (e.g. 13.6 €$/m^2$). For windows, the replacement cost was assumed to be the price of the window as a component, as described in Section 9.3, with costs determined according to prices based on Molio.dk (2018). However, it must be taken into account that the price of a window depends both on the area and on the thermal standard (i.e. energy class) of the window itself.

[5]See description in the text along with Figure 9.4.

Table 9.3: Eligible energy conservation measures (ECMs)

Component	Level	Costs	Note
Roof	+ 95 mm	13.6 €/m^2	$\lambda = 0.37$
Roof	+ 145 mm	+ 7.1 €/m^2	
Roof	+ 195 mm	+ 6.8 €/m^2	
Roof	+ 240 mm	+ 5.1 €/m^2	
Floors	+ 145 mm	55.2 €/m^2	$\lambda = 0.37$
Floors	+ 170 mm	+ 2.6 €/m^2	
Floors	+ 195 mm	+ 1.2 €/m^2	
Ext. walls (cavity)	+ 80 mm	23.6 €/m^2	$\lambda = 0.37$
Ext. walls (cavity)	+ 130 mm	+ 6.9 €/m^2	
Ext. walls	+ 125 mm	202 €/m^2	
Ext. walls	+ 200 mm	+ 43 €/m^2	
Ext. walls	+ 250 mm	+ 37 €/m^2	
Windows	Energy class B	Area-dependent[5]	U-value = 1.4
Windows	Energy class A		U-value = 0.9
Mechanical ventilation	-	80.4 €/m^2	$\eta = 0.85$

To this end, we considered the price of a number of windows with the corresponding size; Figure 9.4 illustrates the concept. Consequently, the price was estimated for each window separately on the basis of the size and the class, using a linear regression model.

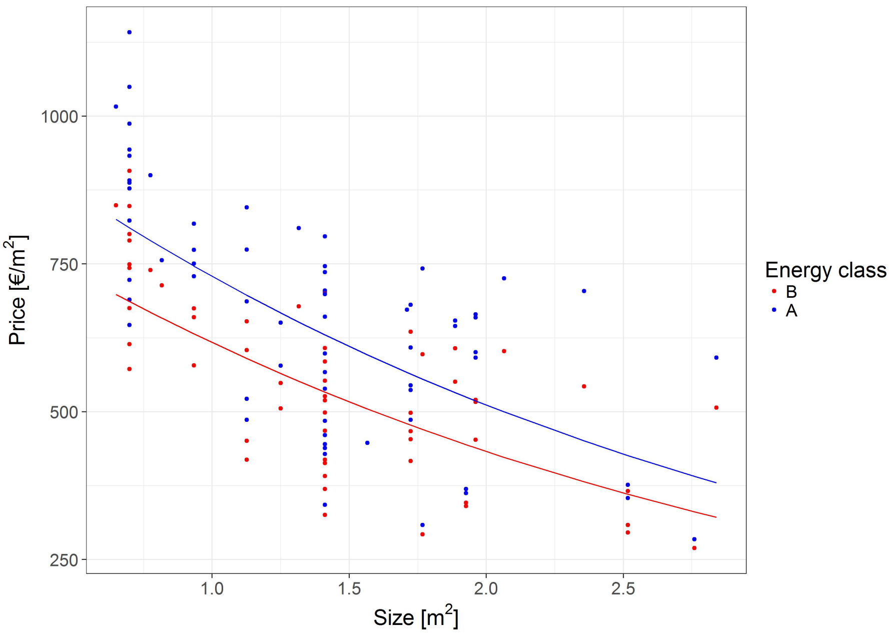

Figure 9.4: Window price depending on the size of the window

9.4.3 DH tariff structure in Aarhus

In Aarhus, the district heating price is based on three components, namely a consumption fee (variable, in [€/MWh]), a capacity fee (fixed, [€/m^2]) and a subscription fee (fixed, [€]) (Danish Utility Regulator, 2018). For the last two components, the first is proportional to the gross heated floor area of the building and refers to capacity payment; the second is fixed annual subscription varying according to the building type (e.g. apartment, detached houses, small commercial buildings, etc.).

Heating system's tariffs related with the three components are usually available in the web-pages of the heat suppliers and are different for each district heating network (Affaldvarme Aarhus, 2018). Figure 9.5 provides a visual representation of breakdown of the costs.

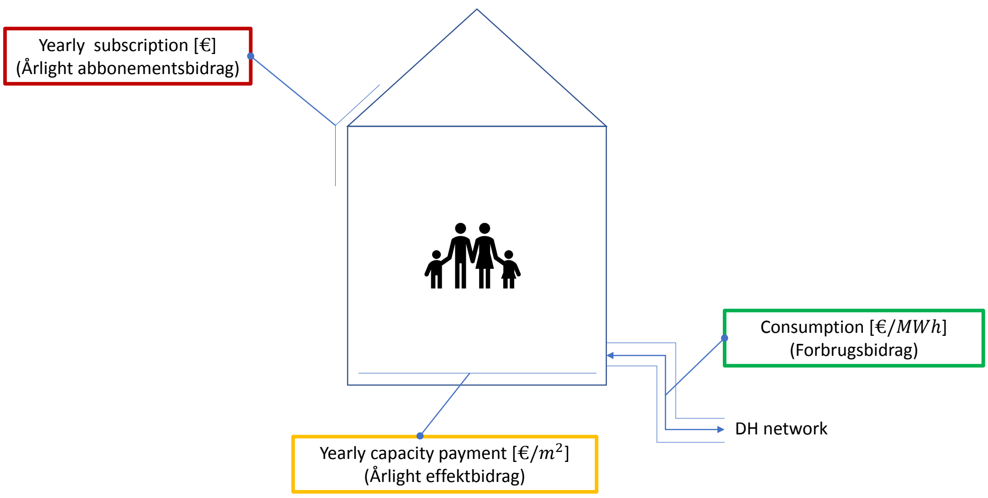

Figure 9.5: District heating cost breakdown for end-user.

The colour coding relates to the nature of the cost components: the consumption fee is variable (*green*), meaning that it depends on the consumption of the building. The capacity payment is (almost) fixed (*yellow*), meaning that is fixed fee for all buildings, a part from some which comply with certain characteristics. For the case of Aarhus, according to the regulations, this component can be halved either if the building was built after BR 10 as low energy class 2015/2020 or if it was built after BR 15 (Affaldvarme Aarhus, 2018). Such arrangement can be considered as a reward for the "best energy performing building". Last, the yearly subscription is a fixed fee (*red*) which relates to the connection to the district heat network. For our case study, we use cost components according to the 2015 tariffs, as reported in Table 9.4 and we assume constant values throughout the horizon of the investigation.

Table 9.4: Heat tariffs for the district heat area of Aarhus, 2015 (Affaldvarme Aarhus, 2015).

Consumption [€/MWh]	Yearly capacity payment [€/m^2]	Yearly subscription [€]
86.43	2.44	126.63

The price of the consumption component for the district heating area of Aarhus, 86.43 €/MWh, is among the lowest compared to other areas in Denmark. On the other hand, considering all the elements, the costs related with consumption (i.e. variable heat cost component) correspond to 84.3% of the total average expenses in a 130m^2 single-family house with an annual heat demand of 18.1 MWh, which is among the largest shares compared with other DH areas, as reported in Figure 9.1 (Affaldvarme Aarhus, 2015).

9.4.4 Case study and scenarios

In relation to the case study, we investigate the cost-effectiveness of investments in heat savings measures according to a *Base case* scenario. For this, we assume a discount rate of 5% for residential investments and we consider only the variable component of the heat cost. The value could be perceived as large, considering that in Denmark the risk-free investment rate is about 3%. However, to account for the expected uncertainty from investments (given e.g. fuel price volatility and regulatory uncertainty), investor socioeconomic conditions and risk attitudes, we adopt a conservative approach and consider a discount rate of 5%.

Furthermore, to consider uncertainties related to relevant input data, we perform sensitivity. We thus define two scenarios where we lower and increase the values for discount rates, respectively *Scenario DR 3%* and *Scenario DR 7%*. Last, according to the methodologies in Eqs.(9.2)-(9.3), we explore the effect of varying heat tariffs on the overall uptake of energy saving measures, acting respectively on the capacity payment (*Cap. reduction*) and on the subscription (*Tot. reduction*).

Table 9.5 summarise the data employed for each scenario; for the heat costs, we refer to the values in Table 9.4.

Table 9.5: Scenarios description.

Scenario name	Discount rate	Cost components considered		
		Consumption	Capacity payment	Subscription
Base Case	5%	✗		
DR 3%	3%	✗		
DR 7%	7%	✗		
Cap. reduction	5%	✗	✗	
Tot. reduction	5%	✗	✗	✗

9.5 Results

In the present section, we first consider the results from the base-case; next, we report the outcomes from the other scenarios in Table 9.5.

9.5.1 Base case

Preliminary check The main driver for the investment lies in the economic profitability of adopting a particular measure, based on the cumulative savings achieved during its entire lifetime. To get a first idea of potentially attractive investments, we calculate the average energy per unit that could be saved each year if an investment of 1 € is made in one of the examined measures. The outcomes in Figure 9.6 highlight that, on average, the annual savings are more attractive for external walls, floors and roofs, while investments in windows and ventilation measures are the least beneficial. Based on the data available, it also results that kWh/€ invested are higher for buildings with lower energy labels (see e.g. E, F, G). Although Figure 9.6 gives an overview of the potential benefit related with different investments, the most cost-effective measure also depend on the characteristics of the measures (e.g. area) and the related savings throughout the lifetime.

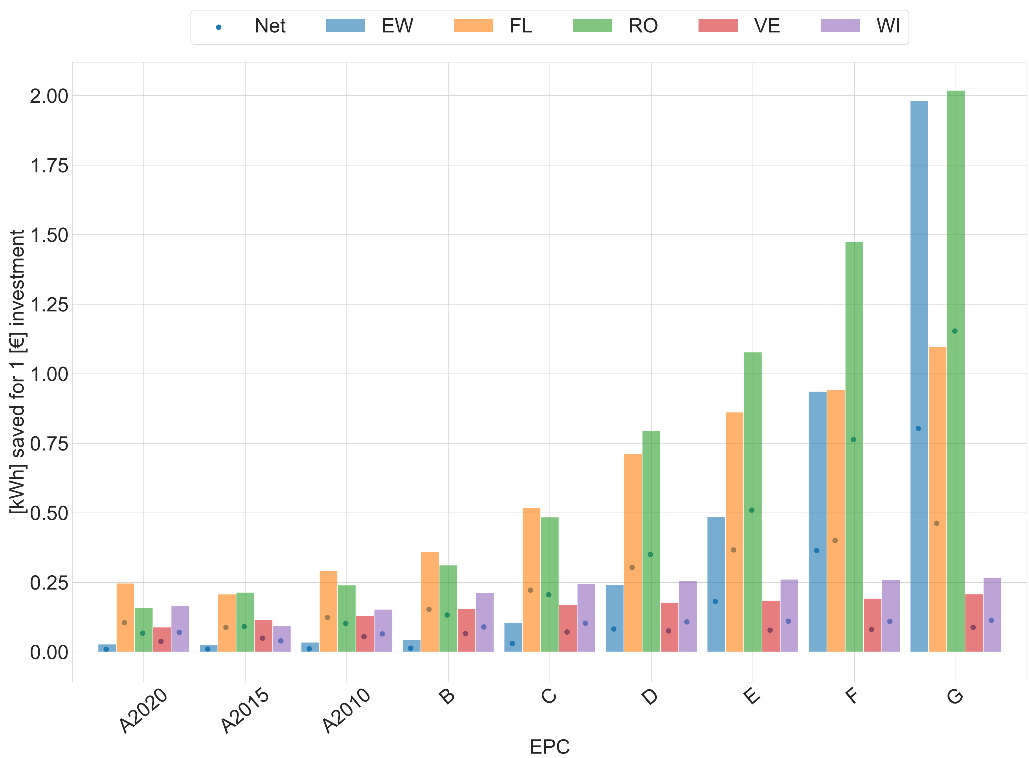

Figure 9.6: Average kWh/year saved for 1 € invested.

Cost-effective cost curves Figure 9.7 illustrate the resulting cost curves for attractive heat saving potentials. The outcomes remark the difference between the gross and net saving data, highlighting a larger positive potential for the first (around 50 GWh) compared to the second (around 9 GWh) approach. The most expensive cost-effective measures for both curves top at marginal cost around 1.7 €/kWh. The total cost-effective savings corresponding to 9.3% and 1.9% of the gross and net heat consumption. In total, we found that 8074 (gross) and 2034 (net) buildings invested in energy conservation measures, with average savings around 6.23 MWh and 4.11 MWh respectively.

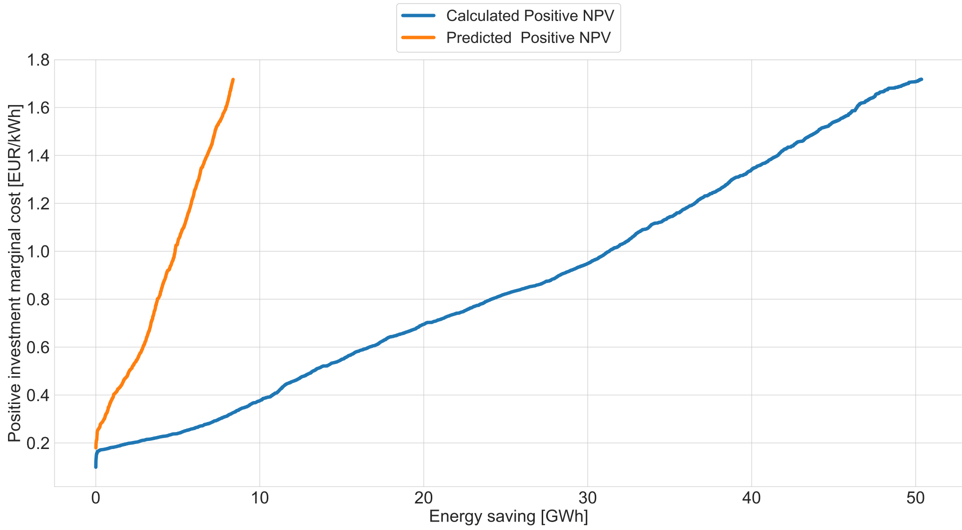

Figure 9.7: Cost-efficient investments cost curves. The orange line denote the net energy saving potential whereas the blue line denote the gross energy saving potential.

Relative energy savings by component In Figures 9.8-9.9 we report the relative energy savings, showing how much each component contributes to the total savings, for a particular building category. The share of the components differs among EPC labels and the gross-net savings approach. The outcomes from gross saving data show that floors and roof constitute the majority of positive investments among all the categories, followed by external walls. Ventilation and windows measures contribute only in part. On the other hand, for the net saving data, Figure 9.9 shows that roofs and external walls are the predominant investments, followed by floors and windows. For this case, investments in ventilation are not deemed attractive and there are no cost-effective measures from buildings with EPC "A2020".

In Table 9.6 we report the total GWh savings resulting from positive investments, according to measure type and energy performance certificate labels. Although we cannot generally compare the absolute values among building categories due to original differences in the sample data[6], we can observe a difference between gross and net savings.

[6]Observing the values in Table 9.6 it would seem obvious that buildings with EPC label D and E have

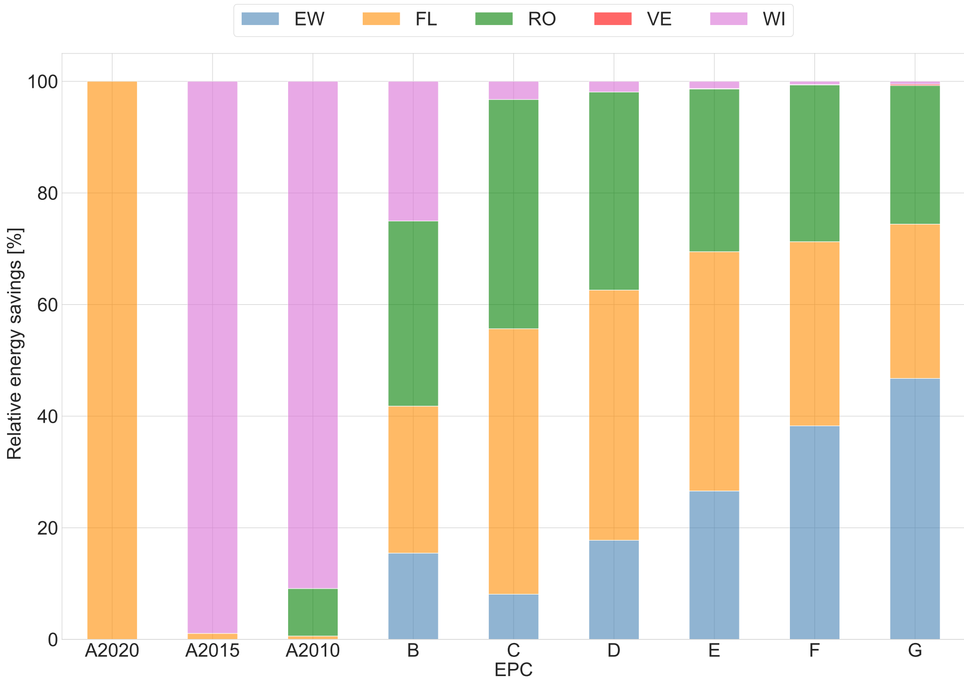

Figure 9.8: Relevance of energy saving investments by component [%], gross savings.

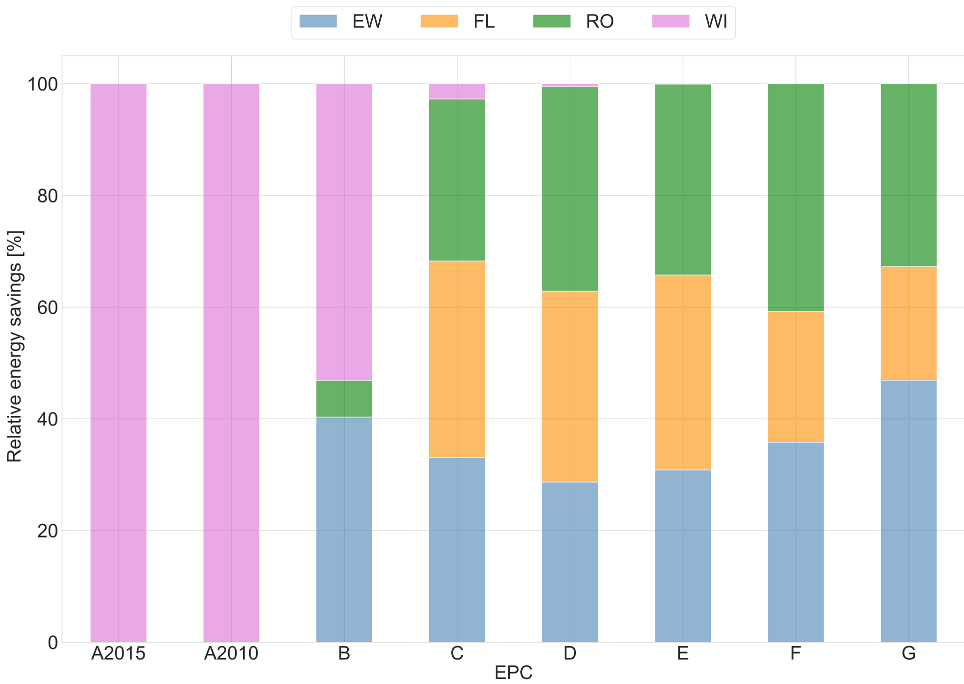

Figure 9.9: Relevance of energy saving investments by component [%], net savings.

Table 9.6 shows that savings investments in building category A2020, already at low levels for the gross approach, are not valuable for the net savings case. Also, we can observe that for the gross savings approach, most of the savings are present in buildings with EPC

the largest potential for positive investments, however this is simply due to the distribution of measures among buildings, presented in Table 9.2, which is indeed biased.

D and E, while the net approach shows a redistribution of positive investments, which are more present in building category E and F. One can also notice the relevant change of scale among the two approaches highlighting that, overall, total positive savings are consistently lower for net savings data by a factor 6. The resulting economic savings can be determined multiplying the consumption heat-cost component by the overall energy savings achieved, according to values as in Table 9.4.

Table 9.6: Summary table for energy savings by component [GWh], gross and net savings.

Component	External wall		Floor		Roof		Ventilation		Windows		Total	
	Gross	Net	Gross	Net	Gross	Net	Gross	Net	Gross	Net	Gross	Net
A2020	0	0	0.001	0	0	0	0	0	0	0	0.001	0
A2015	0	0	0.001	0	0	0	0	0	0.005	0.001	0.005	0.001
A2010	0	0	0.001	0	0.001	0	0	0	0.019	0.005	0.020	0.005
B	0.010	0.003	0.017	0	0.022	0.001	0	0	0.016	0.004	0.066	0.007
C	0.288	0.060	1.692	0.063	1.461	0.052	0	0	0.115	0.004	3.557	0.181
D	2.643	0.556	6.672	0.663	5.283	0.709	0	0	0.284	0.010	14.883	1.938
E	3.963	0.793	6.391	0.897	4.346	0.879	0.012	0	0.191	0.001	14.905	2.572
F	3.833	0.716	3.305	0.468	2.815	0.815	0.007	0	0.056	0	10.017	1.999
G	3.227	0.782	1.907	0.340	1.715	0.546	0.015	0	0.035	0	6.901	1.669
Total	13.966	2.912	19.986	2.433	15.645	3.003	0.035	0	0.724	0.026	50.359	8.375

9.5.2 Scenario analysis

We then investigate on the variation of the outcomes, according to the scenarios presented in Table 9.5. We first observe the total cost-effective energy savings, presented in Figure 9.10. In case we assume a discount rate of 3% (i.e. analysing cost-effective measures from the point of view of a risk-taker investor), the total energy saving potential would reach 95 GWh and 12.6 GWh, for the gross and net savings approach. On the other hand, for a discount rate of 7%, generally reflecting the attitude of a risk-averse investor, the total would be 38 GWh for gross savings and 6.2 GWh for net savings.

In both scenarios where the tariff structure was altered, the total cost-effective energy saving potential increased considerably, reaching gross savings around 69 GWh (11 GWh, net) for the "Cap-reduction" scenario and 96 GWh (22 GWh, net) for the "Tot. reduction" scenario. Hence, allowing the capacity component to be variable, an increase of almost 37% (gross savings) and 26% (net savings) was observed compared to the base case. To assess the impact on the individual ECMs, we considered the pay-back period (PBP)[7], as it provides a simple base of comparison with the expected lifetime of the corresponding ECM (i.e. attractive investment for PBP<lifetime). Figure 9.11 illustrate the sensitiv-

[7] We define the pay-back period as the time required for the investment to break-even.

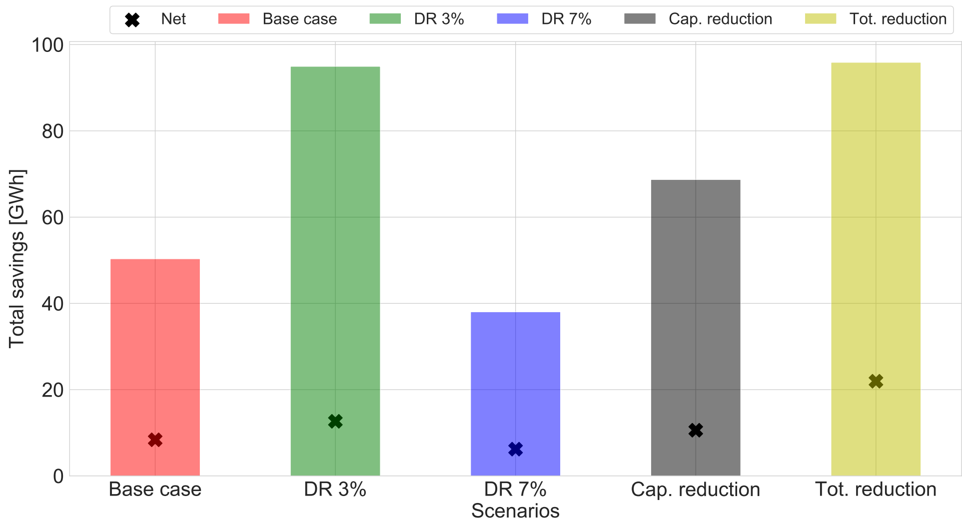

Figure 9.10: Total savings per scenario [GWh].

ity performed: the green bar identifies the lifetime of the building component, while the black and red markers identifies the resulting PBPs for the gross and net savings approaches. The results represent an average over all the positive measures from the base case, investigated under different conditions[8].

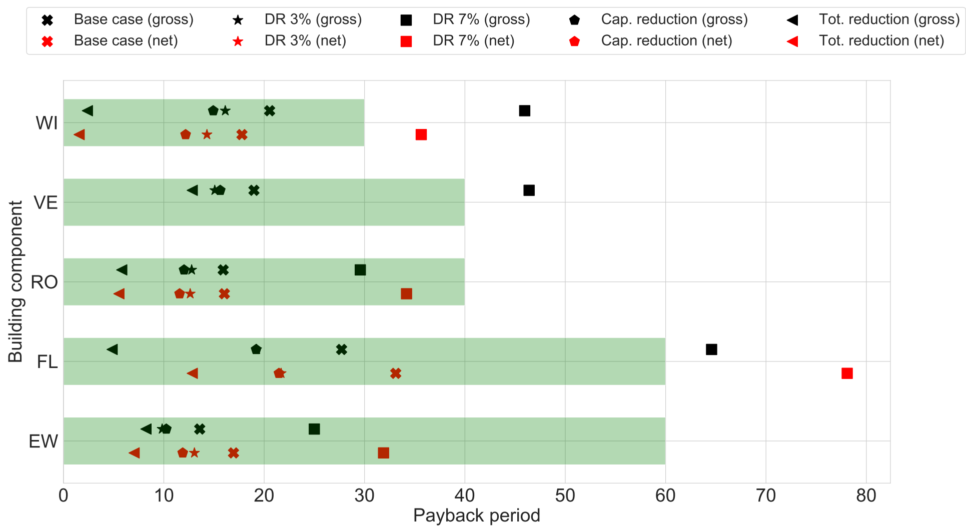

Figure 9.11: Average pay-back period of all cost-effective ECMs by component [Years]. The green bars denote the assumed lifetime of each component.

[8]We follow this assumption due to challenges in doing otherwise. Intuitively, changing an input parameter lead to an increase/decrease on the number of attractive measures, which has an impact on the average payback period. For example, if we decrease the discount rate from 5% to 3%, compared to the base case, various measures which before were not attractive, now they are (See Table 9.7 for relative changes). However, the fact that they were not positive before implied that they were "borderline" attractive, meaning that the pay-back period was either similar or just after the lenght of the lifetime. Consequently, we would have that for a decrease in the discount rate, the number of attractive measures would increase, but the overall average PBP would increase. This would crease confusion for the reader.

For the gross savings case (black markers), Figure 9.11 shows that two scenarios influence most the PBP: DR 7% and Tot. reduction. Assuming a discount rate of 7% leads to non-beneficial investments for almost all the building components, a part from external walls and roofs, as the pay-back period extends over the lifetime. On the other hand, the "Tot. reduction" scenario, where we assumed that all district heat-cost components are variable, leads to a consistent decrease in the value of the average pay-back period.

On the same line, the net savings case (red markers) presents similar results, a part from ventilation measures, which are not attractive. The outcomes highlight that the methodology applied is most sensitive to the "DR 7%" and "Tot. reduction"scenario, which can be identified respectively as the worst and best performing case. The other two cases seems to have a lower impact on the base-case results, with quite some closeness between each other.

Table 9.7 reports a summary, highlighting the increase (+%) or decrease (-%) in the number of positive measures (N°) and on the average value of the pay-back period (PBP), comparing the simulated scenarios with the base case. For instance, assuming a discount rate of 3% leads to an increase of 90% in the number of attractive investments in external walls. Furthermore the average pay-back period, for the same sample of measures which were positive in the base case, decreases of about 27%.

Table 9.7: Relative changes (%) for the simulated scenarios compared to base case, gross savings.

Component	Base		DR3% (%)		DR7% (%)		Cap.red.(%)		Tot.red.(%)	
	N°	PBP	N°	PBP	N°	PBP	N°	PBP	N°	PBP
Ext. wall	1161	13.5	+90	-27	-18	+84	+33	-24	+ 224	-39
Floor	6750	27.7	+48	-30	-44	+133	+35	-30	+ 86	-82
Roof	4875	15.9	+23	-19	-20	+85	+16	-24	+ 153	-63
Ventilation	3	18.9	+267	-20	-33	+144	+200	-17	+ 1567	-32
Windows	1423	20.5	+173	-21	-57	+123	+138	-27	+10172	-88

Considering the size of the sample available, the average value of the PBP might hide some aspects that could worth a deeper analysis. For instance, it would be useful to know if there are measures which are "borderline" (i.e. close to being) cost-effective, as these measures could become attractive if they were subsidised or subject to tax reduction. Hence, we investigate on the distribution of the pay-back periods, to understand which elements to target for possible policy recommendations.

As an example, Figure 9.12 shows the distribution of the pay-back periods for external walls (gross savings approach). The vertical line is the lifetime of the measures, thus any distribution on the left hand side represents attractive investments, while all the data on the right side represent the opposite. We can see that, for the "DR7%" scenario, the pay-back periods are highly gathered between 0 and 20 years, highlighting the small stock of measures which are attractive even in the "worse scenario". On the other hand, the other scenarios present a right tale that extends over a broader range of pay-back periods, continuing even after the limit of the lifetime.

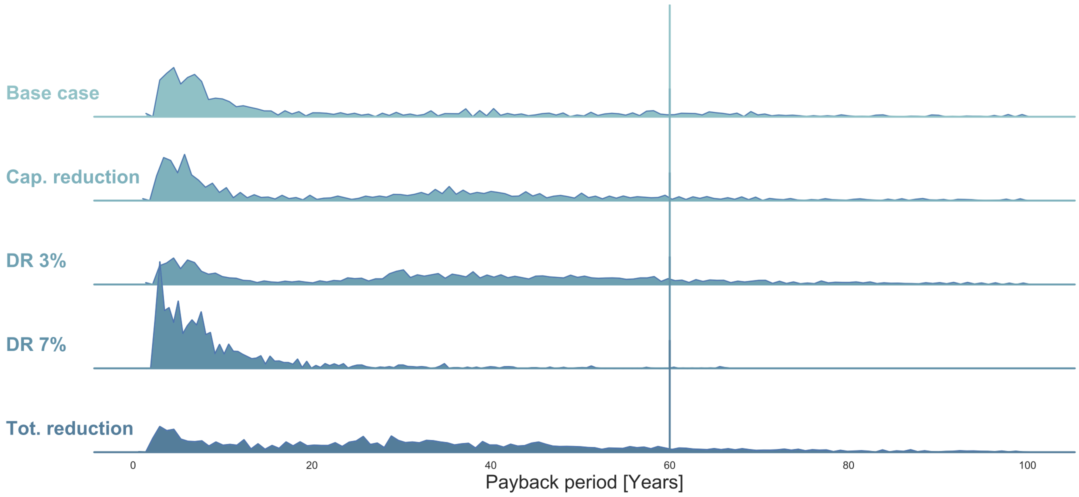

Figure 9.12: Distribution of pay-back periods in the five scenarios for External wall [Years], gross savings. The vertical line denotes the expected lifetime.

The reader should not be mislead by the large size of the distribution of the attractive measures with a short pay-back period for the DR7% case. Although counter intuitive (i.e. one would expect less measures for this case, as it was assessed as the "worst performing"), it follows the logic of the methodology in Section 9.3.2 according to the input data provided. For instance, assuming that for a building there are three possibilities for a more efficient external wall, in the DR7% case (i.e. for a risk averse investor) the model selects the measure with the shortest pay-back period, and disregard the others.

On the other hand, for a DR3% case (i.e. for a risk taker investor), the model considers the various options and select the one which can save more energy in the long-term, even though the measure will be paid off in a longer period of time. This explains the different distribution of the pay-back periods in Figure 9.12 for the scenarios. Also, as the total number of attractive savings measures changes among the scenarios, Table 9.7 reports additional specifics about the distribution for all the other components and the absolute values of the total number of cost-effective investments.

9.5.2.1 Effects of variations in heat-cost components

Last, we investigate further on the effects of varying heat cost components, as we believe that such scenario can provide hints for policy discussion around district heat tariffs and uptake of energy saving measures.

Figure 9.13: Share of heat costs in buildings, based on sample data available.

In Figure 9.13, we report the distribution of the costs bore by the buildings according to the heat-costs components and energy performance certificates, calculated on the bases of the yearly gross consumption[9]. The red bars identify how much the buildings under study spend in relation to heat consumption, the green bars show how much buildings pay for the capacity component, and the light yellow bars identify expenses related with the annual subscription.

Figure 9.14: Share of cost-effective investments in relation to the heat-cost tariff components

[9] As no remarkable difference was observed for the net savings case, we discuss and present only results for the gross savings approach.

We can observe that buildings with the best energy performances (e.g. A2020, A2015 and A2010) have most of the costs related with capacity and subscription payments. On the other hand, buildings with the worst energy performances (e.g. E, F, G) have more costs linked with heat consumption. These figures can be considered as a base for discussion about cost-effective investments in ECMs, according to variability in the heat-tariff components, which we report in Figure 9.14.

Figure 9.14 shows the share of cost-effective investments in relation to the heat-cost tariff components, that is how many investments happens in relation to a particular heat-cost tariff component. At first, we can observe the correlation between the overall costs in Figure 9.13 and resulting savings in Figure 9.14. For buildings with the highest EPCs, we notice that most of the investments happens in relation to the subscription payment. Meaning that buildings with these characteristics would invest more in ECMs if they had the chance to ponderate the cost of the subscription with the possibility of an energy savings investment.

On the other hand, for buildings with lower EPCs, more savings take place in relation to the consumption (red bars). Moreover, in line with the methodologies including the capacity payments, the green bars highlight that if the heat-cost tariff was structured in such a way to reduce the capacity component proportionally to the savings achieved, there would be more cost-effective investments (i.e., size of the green bar > size of the red bar). For the same low EPC buildings, the light yellow bars do not seem to have a relevant impact on the overall share of cost-effective investments.

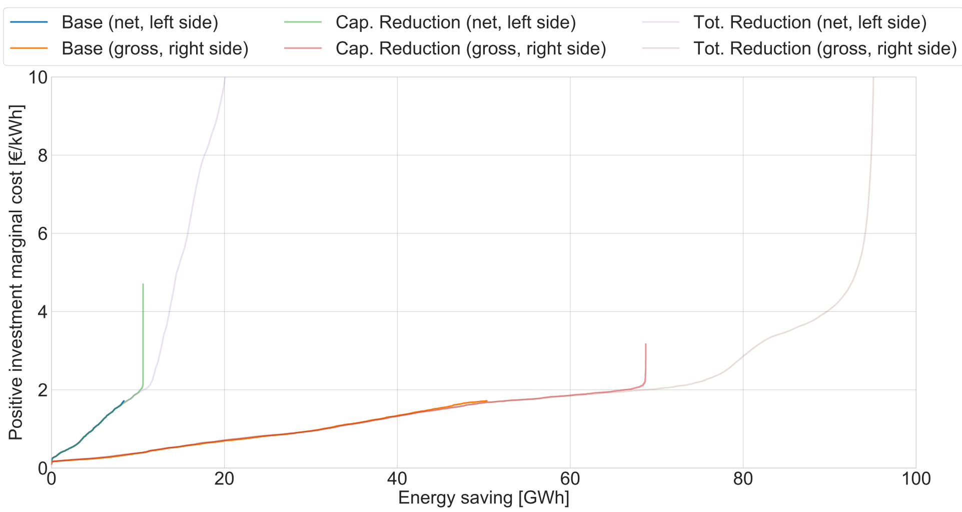

Figure 9.15: Effects of variable cost-components in cost curves

Finally, Figure 9.15 illustrates that exposing the private consumer to both capacity and consumption payments, in regard to district heat tariff, can unlock a wide range of energy savings with different marginal costs. In relation to the heat-cost tariff components, the curves reported show that cost-effective investments can be attractive with different levels of marginal costs according to the case considered. Specifically, making the capacity heat-cost component variable can lead to an increase of factor 2 in the positive cost-effective investments, reaching marginal costs up to 3 €/kWh and 5 €/kWh, respectively for gross and net savings case, and related additional savings amounting to 18.37 GWh and 2.2 GWh, respectively.

9.6 Discussion

9.6.1 Considerations from the building perspective

In the present study, the cost-effectiveness of employing a range of energy-conservation measures (ECMs) was considered. These ECMs included energy-upgrading the building envelope, by means of decreasing the heat consumption in residential buildings.

In addition to the ECMs considered for the study, interior insulation could also offers a way of energy-upgrading the building envelope, given that moisture conditions allow for doing so, which can potentially increase the identified energy savings. On the other hand, neglecting architectural concerns (e.g. facades worthy of preservation) and assuming no physical restrictions on roof insulation (e.g. limited attic space), could likely decreases the potential, leading to a possible overestimation of the results.

In this study, only marginal costs were considered. This implies that the developed ECMs would only be cost-effective, if a building component (e.g. an external wall), was to be renovated anyway. The marginal cost of replacement for a window was assumed to be the full cost (not considering installation, etc.), which can probably be the cause of windows not being very cost-effective measures to replace. However, the marginal cost of replacing a window, with the cheapest window on the market, could be considered to have zero marginal costs, in case the replacement would have taken place anyway. This would obviously have improved the cost-effectiveness of the cheapest windows considered in the study, considerably.

Even though an energy upgrade of the building envelope offers a large gross energy saving potential, post-renovation demand related effects can reduce the net energy saving potentials. To account for this limitation, a linear regression model was used to reflect a more realistic evaluation of the savings available, though it was not considered in depth in the paper. One drawback of the model was that it did not distinguish between different types of demand-related effects, which could affect different ECMs differently: i.e.

the effect of all ECMs was reduced equally in the model. Consequently, the net energy saving potential is subject to uncertainty, as such effects could come in many forms, e.g. increased average indoor temperatures or increased air change rates.

9.6.2 Characteristics and support for non attractive measures

The outcomes show fundamental differences in regard to the gross and net savings approach, which translated in distinct levels of cost-effective measures according to building characteristics. Measures such as external walls, floors and roofs were found to contribute the most to the total stock of cost-effective investments, while mechanical ventilation and windows were found to be less relevant. This is in line with the preliminary check performed in Figure 9.6, where we investigated on the average savings per unit of investment, although the share of investments by EPC differs compared to the levels illustrated. The outcomes are aligned with other studies investigating on the Danish building stock, a part from investments in windows (Zvingilaite, 2013; Zvingilaite and Balyk, 2014; Zvingilaite and Klinge Jacobsen, 2015).

Furthermore, compared to other studies, we provide specifics tailored to the EPCs of the buildings, which display distinct cost-effective measures. The distinction is relevant as it can allow a private consumer to identify, according to the characteristics of her/his household, the most appropriate measure to save energy.

The findings can be useful for policy design, as they identify the target for possible subsidies and support measures. For instance, analysing the outcomes in Table 9.6 it results that most of the measures are cost-effective for buildings with low energy performance classes: on the total 50.35 GWh cost-effective gross savings, only 0.01 GWh are related to buildings with EPC A2020-A2015-A2010-B.

However, as the investments deemed worthy represent only a small fraction of the total potentials available, meaning that many other measures are yet to be attractive[10], subsidies for energy savings investments should be directed unevenly throughout building categories, mostly targeting residents in buildings with EPCs D to G where most of the unexploited potentials still lay.

Also, as the outcomes revealed that overall some measures are more attractive than others, policy support should be directed to the category with lowest investments, for instance targeting mostly windows and mechanical ventilation systems. Last, as the outcomes

[10] Compare the number of potential investments Table 9.2 and the number of cost-effective investments Table 9.6.

revealed that some measures are just borderline non cost-effective (Figure 9.12) and that, among each other, some measures are less attractive than others, policy support should target (i) measures which overall are close to-be cost-effective but not yet there and (ii) measures with few investments, for instance windows and mechanical ventilation systems.

9.6.3 Impact of discount rates

We further analysed the impact of assuming different discount rates, on the uptake of attractive measures. Based on our findings, compared to the base case, assuming a discount rate of 3% leads to a 90% increase in the total GWh of attractive savings, while a value of 7% leads to a 24% decrease. Also, in Figure 9.11 we proved that lower discount rates can shorten the pay-back periods, allowing a faster recover of investments in energy conservation measures.

In this regards, the outcomes have implications on two levels. First, in real terms a lower discount rate can be related with lower taxation rates on loans from banks or other institutions. Hence, local institutions in Aarhus, aiming at fostering the uptake of energy savings interventions in the residential sector, should ease the burden of loans for renovation purposes, offering lower interest rates. Second, when evaluating investments, discount rates are often used as proxies to include details about non-economic barriers and bounded rationality, increasing proportionally the values. Based on these terms, a "practical way" of decreasing the value of the discount rate could be a sensitisation of the inhabitants on the benefits related with energy savings investments in the buildings, linked with the findings from our study. Although in this study we cannot quantify the direct effect of information campaigns in the value of discount rate, a more informed consumer can surely ponderate better the choice of investments in savings measures.

Also, although our results are detailed in regard to building measures and technical characteristics, they disregard the composition of the residents, hence neglecting socio-economic aspects like education, income, behaviours, which have been proven to influence the probability of investments in savings measures (Baldini et al., 2018). If available, such details could be included in the model and enhance the results.

9.6.4 Effects of changes in the district heating tariff structure

Last but not least, the outcomes of the study spark suggestions about relevant policy measures in regard to changes in the heat-tariff structure. During the study we develop a method which reduces the heat-capacity payment proportionally to the energy saved by the measure selected. The methodology thus rewards the investors not only in terms of avoided heat consumption, but also as a mean to decrease the overall grid payments. Ultimately, we consider all the heat-cost components. For the building stock under analysis, we noticed that grid cost components cover a smaller share of the total annual buildings expenditure, compared to expenses for heat consumption. Exception made from buildings with the highest EPCs, the share ranges between 10 and 40%, with smaller values for the buildings with low EPCs (Figure 9.13).

However, when this share is made flexible and heat cost components can be considered in the assessment of cost-effective measures, the total number of investments increase considerably. Specifically, we noticed that when all the cost components are made variable, the related investments in ECMs distribute un-evenly among building EPCs categories (See Figure 9.14). For buildings with high EPCs, most of the investments happens in relation to the subscription payment; for buildings with low EPCs, most of the investments are related to the consumption and capacity components. Intuitively, the best energy performing buildings, with low energy consumption, present most of the attractive investments in relation to the subscription payments. On the other hand, building with low energy performances would not find relevant an hypothetical disconnection from the district heating, but they would benefit from a tariff rewarding investments in savings.

Although advantageous from the side of cost-effective ECMs private investments, such hypothetical heat-tariff structure can create implications at energy system scale for the district heating (DH) companies. A reduction in the capacity costs can have negative implications for the DH company, which has based its asset and investments on a plan of cost recovery. Hence, a decrease of the capacity tariff could hit the revenues of the company, which ultimately might not be able to fully recover the costs. Moreover, for this tariff to work, the peak consumption of the building would need to decrease, as the DH company would set its operation network to satisfy the newly reduced heat demand.

On the other hand, the application of this method can lead to positive implications for the DH producers. Indeed, if the overall demand of the building stock decreases and the savings implemented allow the building to reduce losses, the district heat network could start to supply heat at lower temperatures. This shift would imply lower heat transmission losses and would facilitate the integration of renewable energy sources as supply options. As investments in energy conservation measures would take place on a long time-period, the transition would give time to the DH companies to adjust the plans and operation of the asset, eventually planning ahead for new investments in lower temperature networks or adapting the current network to the new needs, highlighting a synergistic effect between energy savings and DH supply.

9.7 Conclusion and policy implications

In the present paper, the cost-effectiveness of a number of building energy-conservation measures, for a sample of buildings in the district heating area of Aarhus, was investigated from an end-user perspective. Using a building-physics based building stock energy model, heat demands were calculated for each building in the sample individually. Considering individual components in each building, the *gross* energy saving potentials were calculated and associated with the costs of employing various energy conservation measures, presented in terms of marginal cost curves. In addition to the gross potentials, *net* energy saving potentials were also evaluated by accounting for post-renovation demand related effects.

The study analyse cost-effectiveness of energy conservation measures based on net present value of cash flows comparing investments with the cost of heat consumption. In other scenarios, we analyse the effect of different district heating tariffs structures, in relation to the uptake of energy savings..

We found cost-effective gross energy saving potentials summing to 50.4 GWh and related net potentials of 8.4 GWh, corresponding to 9.3% and 1.9% of the current total gross and net heat demand respectively. In light of the difference between gross and net energy saving potential, the actual decrease in heat consumption could be expected to be substantially lower than the one estimated by the building-physical model (i.e. the gross energy saving potential).

Both approaches show maximal marginal cost around 1.7 €/kWh, even though the cost-effectiveness of ECMs varied considerably among building groups with different energy performance. In particular, as expected, the ECMs were most cost-effective in energy-inefficient houses (e.g. EPC D through G).

In general, roofs, external walls and floors were found to be the most attractive measures, while windows and mechanical ventilation systems were found to be the least. This is line with the preliminary check, where the first three measures showed higher savings per unit of investment, hence implying that these components originally were least energy efficient to begin with.

The results show sensitivity to variations in the values of the discount rates, suggesting that total savings can increase up to 90% (3% discount rate case) or decrease of 24% (7% case). From a measure perspective, lower discount rates can shorten the pay-back periods, allowing a faster recover of investments in energy conservation measures. The outcomes of the study spark suggestions about relevant policy measures in regard to changes in the heat-tariff structure. When all the cost components are made variable, we observed a considerable increase in the total cost-effective of investments, with specific energy conservation measures distributed un-evenly among building EPCs categories. Investments in buildings with high EPCs are mostly linked to the subscription payment; for buildings with low EPCs, most of the investments are related to the consumption and capacity components. As such hypothetical heat-tariff structure can create impacts at energy system scale for the district heating (DH) companies, we discuss potential implications, ultimately highlighting a synergistic effect between energy savings and DH supply. Policy makers should thus support renovation costs for the building categories highlighted by the analysis, encouraging end-users to invest in energy conservation measures and contribute to lower energy needs, paving the way for a more sustainable future.

The presented study could be extended in several key directions. From a building perspective, a natural extension would be to increase the temporal resolution of the model, considering heat demand profiles, including peak loads. The analysis could be also extended to all the district areas in Denmark, to assess variation in investments according to local conditions and tariffs. In this relation, the work should also focus on future projections of district heating costs. Another way could be to link cost-effective energy conservation measures with energy system analysis, to investigate on the energy system impact of changes in heat-demand. Ultimately, this study could benefit from an insight on the district heating company side, assessing if and how relevant investments in cost-effective measures, through a modified heat-tariff, can complicate or facilitate the current and future role of district heating networks and energy savings in future energy systems.

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Chapter 10

Conceptual model of the industry sector in an energy system model: a case study for Denmark

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Abstract: The Paris Agreement highlighted that pathways towards a future with fossil fuel independent societies require the transformation of all sectors to reduce the levels of greenhouse gasses emissions. To this end the industry sector, characterised by a high share of emissions and an intense and diversified energy demand, holds a paramount role. In the framework of assessing the transformation of the industry sector towards more sustainable alternatives, due to interdependencies within an energy system, the adoption of measures to reduce fossil fuel use in industry (e.g. efficiency, fuel substitution, electrification and energy cascading) can influence the operation and transformation of the energy system. To this end, the study proposes a method to simulate and optimise operational aspects of the industry sector at high level of details. The conceptual model is then integrated in an established bottom-up energy system model, creating a benchmark for analyses that can focus simultaneously on the impact of changes in the industry and in the energy sector on a system wide scale. On the practical side, by mean of a Danish case study, the paper sheds light on particular characteristics of the industry sectors, focusing on the structure of industrial energy use in regards to end-use processes, aspects of energy consumption, and measures for fossil fuel reduction. Considerations sparking from the analysis show the potential applicability of energy cascading, electrification and fuel substitution for industrial processes, engaging elements and technologies interlinked within the energy system. Given the theoretical approach proposed, similar considerations can be investigated for other case studies, exploiting the simultaneous optimisation of power, district heat, industry dispatches and characteristics. In this framework, the transformation of the energy use in industry sector can be simulated according to more stringent policies capping CO_2 emission levels and specific support schemes, paving the way for carbon neutral societies and a more sustainable, yet resilient, future energy system.

Keywords: Industry modelling · Energy savings · Fuel substitution · Electrification · Integrated energy system model Balmorel · Process heat

10.1 Introduction

In light of the recent Paris Agreement, which highlighted the importance of decreasing the use of fossil fuels in energy intensive sectors for greenhouse gasses (GHG) emissions reduction purposes, the necessity to aim at carbon neutral societies and switch to 100% renewable energy systems is a clear goal. In Europe, similarly to other international contexts, two sectors stand out for substantial energy consumption and related GHG emissions: power and industry. In the last years the power sector has experienced a considerable transformation, with multiple interventions designed to shift primary sources of energy production towards more sustainable alternatives. Policies implemented and innovations have thus fostered renewable technologies, energy efficiency and sustainable fuels, reducing considerably the energy-production related GHG levels.

Compared to the ongoing transformation in the power sector, measures for reducing GHG emissions in industry lags. With more than 125 TWh of electricity consumption, 851 TWh of fossil fuels used for energetic purposes and 671 TWh of fossil fuels feedstock, in 2010 the industry sector accounted for almost 25% of the total final energy consumption in the European Union (EU) (Eurostat, 2017a). The related GHGs corresponded to 9% of the total EU28 emissions stock, as both European statistic institution (Eurostat, 2017b) and researchers confirms (Lechtenbohmer et al., 2016). The need for action to reduce fossil fuels in industry is clear, but several barriers exist. One essential difficulty is the heterogeneity of the sector, given the diversity of processes involved and a worldwide variation in facilities. Furthermore trade exposure, cost sensitivity, and long lived facilities have contributed to a slow adoption rate of interventions to reduce industrial emissions (Bataille et al., 2018).

Three main established technology options to reduce industrial emissions are available: efficiency, fuel substitution and electrification. Energy cascading - that is, the use of high quality heat from a source to be reused for other processes or for general heating - can also be considered. These measures are also referred as "decarbonization lite" (Bataille et al., 2018), even though the true meaning of the word can be discussed, as some options (e.g. biomethane) actually include carbon. Applied examples of electrification (Lechtenbohmer et al., 2016), energy efficiency (Li and Tao, 2017) and fuel substitution (Rehfeldt et al., 2018) show successful application of these options to reduce industry related GHG emissions; furthermore, other studies focusing on future implementation of electrification (IRENA, 2014) and fuel substitution (International Energy Agency, 2012), forecast an intensive use of these measures for future scenarios.

Due to the interdependencies within an energy system, the adoption of measures to reduce fossil fuel use in industry influence the operation and transformation of the energy system. Intuitively, an increased electrification of industrial processes leads to an increase of the electricity demand that, consequently, implies changes in the operation of the energy system (e.g. transmission, power plant operation and investments). Similarly, energy efficiency might lower the need for fuels and electricity; energy cascading can result in similar impacts, potentially providing heat to other sectors in the form of district heat. Regarding fuel substitution, the need for gas and especially renewable gasses in industrial processes, correlates to the options to produce (biogas upgrading) and deliver (gas infrastructure) these gasses by the overall system. Hence, when considering interventions to reduce industrial emissions, it is paramount to study the impact, benefits or challenges on an energy system. Given the current state of industry modelling in existing bottom-up energy system models, this is not always possible.

Models of this type often represent and simulate industry in an aggregate way, neglecting the complexity of the different industry branches or the structure of the processes with regard to input fuels and potentials to abate emissions. Other relevant details, such as temperature heat levels, fuel use characteristics and temporal profiles of energy consumption, are also mostly disregarded. Consequently, analyses based on these models can sometimes fail to report correctly the impacts of changes in the industry sector and can lead to misleading results, both in terms of policy design and energy system operation and planning.

Our study is thus motivated by the following research questions. Which aspects characterise the unique structure of the industry industry sector, in terms of fuel use, processes and characteristics about temporal energy consumption? How can we adequately model such an heterogeneous sector and integrate it in established bottom-up energy system models? How can this conceptual model be used to perform reliable and thorough analyses on GHG emission mitigation measures in the industrial sector?

To address these research questions, we select the energy system model Balmorel (Balmorel, 2018) and, within this framework, we propose a conceptual model to represent the industrial sector. To apply the method we focus on Denmark, an European country that is striving to find solutions to reduce GHG emissions, aiming at a fossil independent future in 2050, focusing intensively on the industry sector (Danish Energy Agency, 2017). Applied cases on a local scale show the convenience of reducing fossil fuels use through energy cascade (Buhler et al., 2017), electrification (Danish Energy Agency, 2014a), energy efficiency interventions (Buhler et al., 2016) and fuel substitution (Jensen et al., 2017). Although the studies indicate promising possibilities, none of the investigations considered a system wide context of changes in the industry sector. To this end, we consider Denmark as a case study.

This paper contributes to the field by developing novel methods, useful to draw practical findings for researchers, industrial institutions and policy makers. On the methodological side, the contribution of the paper consists of (i) proposing a detailed conceptual model of the industry sector and (ii) integrate such model in an established energy system model, creating a benchmark for analyses that can focus simultaneously on the impact of changes in the industry (e.g. energy efficiency, electrification, fuel substitution) and in the energy sector (e.g. renewables, energy efficiency) on a system wide scale. On the practical side, by mean of the case study, the paper sheds light on particular characteristics of the industry.

By providing a detailed conceptual model of the industry sector considering structure of the processes with regard to input fuels, temporal profiles of energy consumption and options to reduce fossil fuels use, the paper narrows the knowledge gap on modelling and representation of the industrial sector in bottom-up energy system models.

The remainder of the paper is structured as follows. In Section 10.2, we present the current status of industry modelling in bottom-up energy system models. In Section 10.3, we present the methods developed. In Section 10.4, we introduce the case study and in Section 10.5 we discuss implications from the study. We conclude in Section 10.6, highlighting the relevant findings and suggesting future research.

10.2 Literature review

When investigating the impact of energy-related interventions in diverse sectors of the energy system (e.g. household, industry), it is fundamental to use tools that consider details such as the fluctuating component of energy production and consumption, given the evermore increasing share of renewable energy sources in the recent energy systems. To this end bottom-up energy system models, including technological explicitness and detailed temporal variation, are the most suitable tools for the task (Herbst et al., 2012).

The literature proposes a variety of bottom-up models suitable for different analyses, with characteristics varying according to the focus (Connolly et al., 2010) or the geographical target (Hall and Buckley, 2016). Among the existing models, only a few consider the industry sector. Moreover, the level of details considered varies, in regard to disaggregated energy consumption, fuel types, temporal profiles of demand and interaction within the energy system. Some models, among others EnergyPLAN (Aalborg University, 2018) and E4cast (Syed and Penney, 2011), consider the industry as an aggregated sector, with demand data defined on an annual level (TWh per year) with no hourly distribution. Also, the energy model MiniCAM operates on a very aggregated level, without representing specific technologies, but rather considering broad classes of technologies aggregated by sector (transportation, buildings, industry) and secondary fuel-type (liquids, gas, coal, biomass, electricity, hydrogen) (Brenkert et al., 2003). Oppositely, models like ESME (ETI), consider more details about the industry, including use of energy in industry segmented into various sectors (Iron, Steel and non-ferrous metals; chemicals; metal products, machinery and equipment; food, drinks and tobacco; paper printing and publishing; cements, ceramics, glass and lime; refineries; agriculture and other industry) and generic categories of production processes (High and low temperature process, drying and separation, motors, space heating and other) (Heaton, 2014).

Although different models feature different characteristics with more or less depth, to our knowledge, none of the existing bottom-up energy system models represents the industry sector in a great level of details, in regard to input fuels, temporal profiles of energy consumption, end-use and tailored options to reduce the use of fossil fuels. Therefore, compared to previous models, in this study we propose an enhanced version of industry modelling, focusing on detailed characteristics of the sector while still considering the connections to the electricity and heat supply system. First, we propose an extension of an existing energy system model to include industry as a disaggregated sector. After, by mean of the study case, we shed light on the 'black box' of industry, proposing insights on the energy consumption in different branches by fuel and end-use or on the temporal variation of energy consumption at an hourly rate.

10.3 Methods

10.3.1 Balmorel: energy system model

Among the tools available in the literature (Connolly et al., 2010), the energy system model Balmorel is adopted for the analysis (Balmorel, 2018). Balmorel is an open source, mostly linear energy system model that optimises investments and operation of power plants, storage devices and transmission lines for geographical areas that can be defined by the user (Wiese et al., 2018). The model considers a set of neighbouring countries operating in an interconnected electricity market (e.g. Germany, Sweden, Norway, Denmark, Finland). Each country is composed by one or several regions, among which electricity can be traded and transmitted, with limits imposed by given transmission capacity. Each electricity region is then divided into several district heating areas (DH); heat transmission among such areas is not allowed.

Balmorel considers time according to years, seasons (often applied for weeks) and individual time units (often applied for hours); the time horizon and time resolution are selected according to the requirements of the analysis.

The model relies on a set of exogenous input data, including existing capacities of electricity and heat generation technologies, transmissions lines and heat and power demand. Energy generating technologies include back-pressure and extraction combined heat and power plants (CHP), heat pumps, storage devices (for electricity and heat), and renewable based production technologies (hydro, wind, solar). Additional key assumptions on fuel prices, CO_2 costs, taxes and support schemes can also be specified.

The model allows to simulate scenarios where demand and supply of electricity and heat are balanced. Operation and investments are optimised considering local generation vs. import/export, demand price elasticity and other characteristics typical of energy systems (Münster et al., 2012). For the simulations, Balmorel considers various "operation modes" with different functionalities. In one mode, the model finds economically efficient dispatches of an existing set of technologies; in another mode, the model has the possibility to dispatch energy using the existing set of technologies but also investing in new technologies and decommission the old asset. In the last mode, the model considers both operation modes (i.e. dispatch and investments) and includes the possibility to simulate different consecutive years (often referred as "rolling horizon"). The choice of the simulation mode varies according to the focus of the analyses, thus allowing to optimise (i) the operation of an existing and defined power system or (ii) dispatches and investment of existing and new power plants, for future energy system. When investing in a new technology, the model considers the discounted investment costs, based on lifetime and discount rate.

The model is supplemented with several addons that allow for specific investigations (Wiese et al., 2018) and has been previously applied for a wide range of studies, such as integration of renewable technologies in the energy mix (Ball et al., 2007), analysis of market conditions (Jensen and Meibom, 2008), policies implementation (Karlsson and Meibom, 2008), future role of district heating (Münster et al., 2012) and impact of energy efficiency technologies in the energy system (Baldini and Trivella, 2017).

10.3.2 Modelling of the industry sector

10.3.2.1 Novel approach

The current version of the energy system model Balmorel considers the industrial energy consumption only as a part of the overall electricity and district heat demand, without specifying absolute values or assigning hourly profiles of consumption. The model does not differentiate diverse industrial demands, meaning that details about input fuels and process heat demands are not considered.

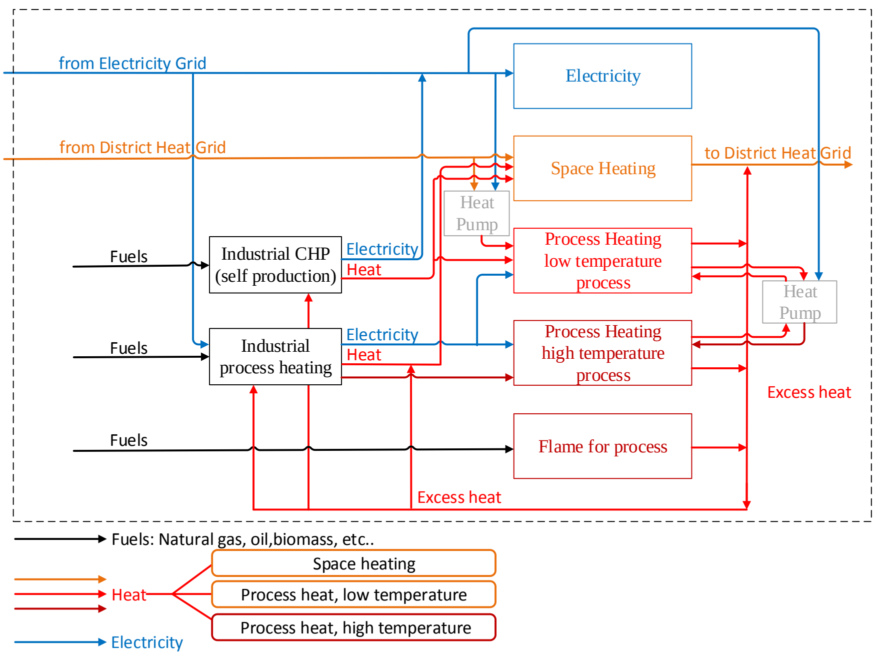

Figure 10.1: Schematic of industry sector representation in Balmorel

Such configuration does not allow specific analyses targeting detailed processes in the industrial sector. To this end, the structure proposed in Figure 10.1 represents a novel approach, with a clear split of the diverse industrial demands. The concept is versatile and flexible to be adapted for diverse industry branches (e.g. manufacture, agriculture).

The novel approach considers details about the electricity demand of different industrial end-uses, facilitating the investigation of tailored end-use specific options (e.g. savings) aiming at reduce the use of fossil fuels. Electricity can be either supplied by the grid, or it can be self-produced in on-site industrial plants. Electricity is also used to run heat pumps, either to satisfy the heat demand, or to boost the quality of heat for specific processes.

Heat, originally considered only as district heat demand, now includes three temperature levels: space heating, process heat low temperature and process heat high temperature (See Table 10.3 for specifics). Heat, from district heating (DH) or excess heat, can be upgraded (i.e. the temperature is increased) using appropriate heat pumps. This means that one could use: (i) excess heat from a high temperature process directly or through a heat pump for district heat and low temperature process, (ii) excess heat from a high temperature process to preheat (partly heat) the heat input for high and low temperature process (depending on the temperature considered for low and high temperature processes) and (iii) heat from district heating to provide heat to a low temperature process (via heat pump). The use of excess heat for district heat or district heat for supplying process heat is limited to cases where a DH network is available (i.e. industrial process in proximity to a DH grid).

Fuels, for energy or feedstock purposes, are considered as input for energy conversion technologies in the industrial structure. Each technology is designed to run mainly with a distinct fuel, although it can potentially shift the input according to constraints imposed in the model (e.g. limitation on process emissions, taxes on carbon based fuels or fuel upgrade, for example from natural gas to biogas). This specific facilitates the investigation of CO_2 reduction options for the industrial sector.

10.3.2.2 Mathematical model

The integration of the industry sector impacts the different constraints of the energy system model, according to the novel structure proposed. Hence, the mathematical formulation presented should be considered as an extension of the base mathematical model developed for Balmorel (Balmorel, 2018). Table 10.1 reports the variables and parameters used in the modelling.

Table 10.1: Nomenclature for the industry modelling: parameters (upper part) and variables (lower part)

Name	Unit	Description
C_{af}^{fuel}	€/GJ	Fuel price
$C_{ag}^{O\&M}$	€/MWh	Operation and maintenance costs
C_{ag}^{inv}	€/MW	Investment costs
Λ_c	-	Annuity
$C_{ag}^{tax-inv}$	€/MW	Tax on investment costs
$E_g^{CO_2}$	kg/GJ	CO_2 emission coefficient
$C_c^{tax-CO_2}$	€/kg	Tax on CO_2 emissions
$C_{fc}^{tax-fuel}$	€/GJ	Tax on fuel consumed
$C_{ag}^{tax-gen-ph}$	€/GJ	Tax on heat process generation units
$C_{ast,us}^{up-step}$	€/MWh	Cost of reduced consumption
$C_{ast,ds}^{down-step}$	€/MWh	Cost of increased consumption
C^{infs}	€	Infeasibility penalty
De_{rst}^{ind}	MWh	Industrial electricity demand
De_{rst}^{res}	MWh	Residual electricity demand
$De_{rstl}^{ind-elm}$	MWh	Industrial electricity demand by element
COP_{gb}	-	Coefficient of performance
Dh_{ast}^{res}	MWh	Residual district heat demand
Ph_{astb}	MWh	Industrial process heat demand
Q_{ag}^{ph}	MW	Capacity installed of process heat technology
F_g^{eff}	-	Fuel efficiency
F_{cf}^{MAX}	GJ	Maximum fuel consumption per country
$LIM_c^{CO_2}$	kg	Maximum CO_2 emissions per country
q_{agstb}^{ph}	MWh	Process heat generation
q_{agb}^{ph-new}	MW	New capacity installed for process heat
f_{agstb}^{rate}	MWh	Fuel consumption rate
$\Delta_{ast,low}^{low}$	MWh	Slack variable lower bound
$\Delta_{ast,up}^{up}$	MWh	Slack variable upper bound
p_{rgst}	MWh	Electricity generation
q_{agst}^{DH}	MWh	District heat generation
$q_{agstb,ds}^{ph-flex}$	MWh	Flexible process heat demand, down steps
$q_{agstb,us}^{ph-flex}$	MWh	Flexible process heat demand, up steps

Objective function In Balmorel, the value of the objective function reflect the total cost faced by the system to satisfy the energy demand, while complying with the constraints imposed. The costs included in the objective function vary according to the "optimisation mode" selected, ranging from costs of only dispatch to costs of both dispatch and investments. In both modes, the total costs includes considerations about transmission, taxes and emission pricing. Hence, the value of the objective function can be interpreted as the least-cost solution to satisfy the energy demand, operating an asset available and (if considered) investing in new technologies.

To be consistent with the structure of the model, all industry-related costs (i.e. both operation and investments) are added to the main objective function. The costs include fuel consumption during the year (Eq.(10.1)), O&M of process heat technologies (Eq.(10.2)), investment in new technologies (Eq.(10.3)), taxes on investments (Eq.(10.4)), taxes on emissions (Eq.(10.5)), taxes on fuel consumption (Eq.(10.6)), taxes on production of process heat (Eq.(10.7)) and eventual changes in consumers' utility relative to process heat consumption (Eq.(10.8), Eq.(10.9)). Slack variables are added for detecting infeasibilities (Eq(10.10)).

As the goal of the model is to satisfy the energy demand according to the least-cost combination, including Eqs.(10.1)-(10.10) to the objective function in Balmorel guarantees that all costs related with industrial energy consumption are part of the optimisation process.

$$+\sum_{a,g,f,s,t,b} C_{af}^{fuel} 3.6 q_{agstb}^{ph} \tag{10.1}$$

$$+\sum_{a,g,s,t,b} C_{ag}^{O\&M} q_{agstb}^{ph} \tag{10.2}$$

$$+\sum_{a,g,c,b} q_{agb}^{ph-new} C_{ag}^{inv} \Lambda_c \tag{10.3}$$

$$+\sum_{a,g,c,b} q_{agb}^{ph-new} C_{agb}^{tax-inv} \Lambda_c 10^6 \tag{10.4}$$

$$+\sum_{a,g,c,s,t,b} E_g^{CO_2} 3.6 f_{agstb}^{rate} C_c^{tax-CO_2} \tag{10.5}$$

$$+\sum_{a,g,c,s,t,f,b} C_{fc}^{tax-fuel} 3.6 f_{agstb}^{rate} \tag{10.6}$$

$$+\sum_{a,g,s,t,b} C_{ag}^{tax-gen-ph} 3.6 q_{agstb}^{ph} \tag{10.7}$$

$$+\sum_{a,s,t} \sum_{down-step} q_{ast,ds}^{ph-flex} C_{ast,ds}^{down-step} \tag{10.8}$$

$$-\sum_{a,s,t} \sum_{up-step} q_{ast,us}^{ph-flex} C_{ast,us}^{up-step} \tag{10.9}$$

$$+\sum_{a,s,t} (\Delta_{ast,low}^{low} + \Delta_{ast,up}^{up}) C^{infs} \tag{10.10}$$

According to the logic of the model, the equations are considered for each area a, with the energy producing technologies g and fuels f available, during the seasons s and time steps t simulated. The index b represents the different temperature levels of process heat, namely space heat (SH), process heat low (PHL) and process heat high temperature (PHH). The indexes us and ds represent the up and down steps in the elasticity demand, while the indexes *low* and *up* refer to the upper and lower bounds when considering infeasibilities for the equations.

Electricity balance As illustrated in Figure 10.1, the industrial electricity consumption De^{ind}_{rst} related with a region r is added to the electricity balance equation in Balmorel according to Eq.(10.11),

$$\sum_{g} p_{rgst} = De^{res}_{rst} + De^{ind}_{rst}. \tag{10.11}$$

where De^{res}_{rst} is the hourly profile of electricity demand not related with industry (residual). The demand in the industry sector can be satisfied with electricity from the grid or self-production ($p_g, \forall g \in G^{ind}$) and is related with the use of heat pumps (HP) and processes/end-uses ($De^{ind-elm}_{l}, \forall l \in L = \{heatpump, processes\}$):

$$\sum_{l} De^{ind-elm}_{rstl} = De^{ind}_{rst}. \tag{10.12}$$

The heat pumps generate heat for the different temperature levels and are related with the electricity use according to Eq.(10.13),

$$De^{ind-elm}_{rst,HP} = q^{ph}_{agstb}/COP_{gb}. \tag{10.13}$$

where q^{ph}_{agstb} is the heat generated from the heat pumps suitable for the temperature levels (SH, PHL, PHH), and COP_{gb} is the coefficient of performance.

District heating balance With the addition proposed, the total energy system district heat balance now considers also the space heat demand for industrial purposes provided by the district heating network Ph_{astb} with *b=SH*. The technologies g producing heat satisfy the total district heat demand:

$$\sum_{g} q^{DH}_{agst} = Dh^{res}_{ast} + Ph_{astb} \tag{10.14}$$

where Dh^{res}_{ast} is the hourly profile of the residual energy system district heat demand, not related with industry.

Process heat balance As presented in Figure 10.1, the process heat demand is fulfilled with a different set of technologies g: district heating grid, self production and other processes for space heating (set G^{ind-SH}); heat pumps and industrial processes for low and high temperature process heat (sets $G^{ind-PHL}, G^{ind-PHH}$). Eq.(10.15) imposes that, at every time step, the production from a set of different technologies meets the process heat demand at the temperature level proposed ($b \in B = \{SH, PHL, PHH\}$). Additional variables ($q^{ph-flex}_{agstb,ds}, q^{ph-flex}_{agstb,us}$) allow flexibility in the demand (up and down), while slack variables $\Delta^{low}_{ast,low}, \Delta^{up}_{ast,up}$ are inserted for modelling purposes.

$$\sum_g q^{ph}_{agstb} = Ph_{astb} - \sum_{down-step} q^{ph-flex}_{agstb,ds} + \sum_{up-step} q^{ph-flex}_{agstb,us} - \Delta^{low}_{ast,low} + \Delta^{up}_{ast,up} \tag{10.15}$$

Process heat technologies related constraints Additional constrains are introduced to reflect technical functioning of the process heat technologies. The fuel consumption rate is fixed by Eq.10.16, where F^{eff}_g is the fuel efficiency of technology g. Eq.(10.17) imposes limits on the production, i.e. at any time production q^{ph}_{agstb} can exceed capacity Q^{ph}_{ag}.

$$f^{rate}_{agstb} = q^{ph}_{agstb}/F^{eff}_g \tag{10.16}$$
$$q^{ph}_{agstb} \leq Q^{ph}_{ag} \tag{10.17}$$

Eq.(10.18) and Eq.(10.19) impose a cap on fuel consumption (F^{MAX}_{cf}) and CO_2 emissions ($LIM^{CO_2}_c$) from process heat production per country. The same constraint in Eq.(10.19) can be used to cap NO_x and SO_2 emission. The equations can be used to investigate the industrial energy mix while complying with future goals on emission reduction and fuel substitution.

$$\sum_{g,s,t,b} 3.6 f^{rate}_{agstb} \leq F^{MAX}_{cf} \tag{10.18}$$
$$\sum_{acgstb} E^{CO_2}_g 3.6 f^{rate}_{agstb} \leq LIM^{CO_2}_c \tag{10.19}$$

10.3.3 Modelling of fossil fuel reduction options

From a modelling point of view, the addition of options to reduce fossil fuels for industry influences the optimisation in different ways.

The electrification of the industry implies a shift from fossil fuel to electricity-based processes. Modelling wise, this means that a new set of process-heat technologies g, based solely on electricity $f \in$ F=$\{Electricity\}$, competes with the existing fuel-based technologies (See Eq.(10.15) and Eq.(10.16)). The criteria for the competition can be economic (e.g. the cheapest option for the system, based on Eqs.(10.1)-(10.10)), environmental (e.g. cap on CO_2 emission, see Eq.(10.19)), or policy based (e.g. imposing a share of electrified industrial processes in future energy systems, see Eq.(10.18)). Given the constraints imposed, the model then decides the optimal level of investments and operation of the technologies in the energy system.

The same method applies for the fuel substitution when investigating the potential use of renewable gasses, biomass and biogas. For this option, the model can change the fuel input in existing technologies from the fuels currently in use to more renewable options.

Energy cascading (or excess heat) can be considered a free source of heat for the processes. As a preliminary approach, 'blocks of energy' are thus made available for processes at different temperature levels, acting as free energy in Eq.(10.15) to satisfy the process heat demand. As the availability of excess heat sources is related to the geographical location of the source (being e.g. an industry or a district heat network), the energy made available must be linked with the geographical limitation of the modelling framework (i.e. excess heat from an industry can be used in a DH network only if it is in proximity). Recent findings from studies on Danish industrial excess heat sources (Buhler et al., 2017), identification of cases for excess heat utilisation using GIS (Buhler et al., 2018b) and spatio-temporal analysis of industrial excess heat as resource for district heating (Buhler et al., 2018a), show that detailed data about excess heat can be determined in relation to the location of the process heat demand.

Energy savings in the industrial sector have a direct effect on process heat and industrial electricity demand. Based on the method proposed by Baldini and Trivella (2017), the savings can be added as a complementary option. The model has the choice to either supply the energy demand (both electricity and process heat) with the current set of technologies or to invest in energy saving measures, that lower energy needs. The optimisation process selects the option that minimise the total costs, while complying with the restrictions. Estimates on the cost of energy saving measures are available from the Danish Energy Agency (2015) and are presented in Table 10.5, aggregated by end-use. In case the costs are not discounted, the model should include considerations about lifetime and discount rate. Investments in energy saving measures impact Eqs.(10.1)-(10.10) for the investment costs and Eq.(10.11), Eq.(10.14), Eq.(10.15) for the reduction on electricity, DH and process heat demand. The investment depends on the value of the savings achieved during the lifetime versus the cost of the corresponding energy demand.

10.3.4 Data processing

With the intention of unifying various data sources to have a clear, detailed, and up-to-date dataset about industrial energy consumption, we perform data processing. In regard to the case study considered, the approach used in data gathering and analysis first considers details about fuel consumption by sector and end-uses. The Danish version of the international nomenclatures NACE[1] (Rev. 2, ISIC, Rev. 4) is the Dansk Branchekode DB07 (Danish Industry Classification 2007), a statistical classification of economic activities that categorises each enterprise based on its main activity. The energy consumption by industry group and fuel type is published by Statistics Denmark on a yearly basis (Statistics Denmark, 2017). The data are available according to the industry structure based on the db117-grouping, a national classification that organises Danish companies based on their Danish Branchcode (DB07) into 117 activity groups. This structure is widely applied by Danish institutions for identifying the affiliation of companies (Danish Energy Agency, 2014b) and is often used in other national data sources, for example about conversion potential in industry (Danish Gas Technology Center, 2013a).

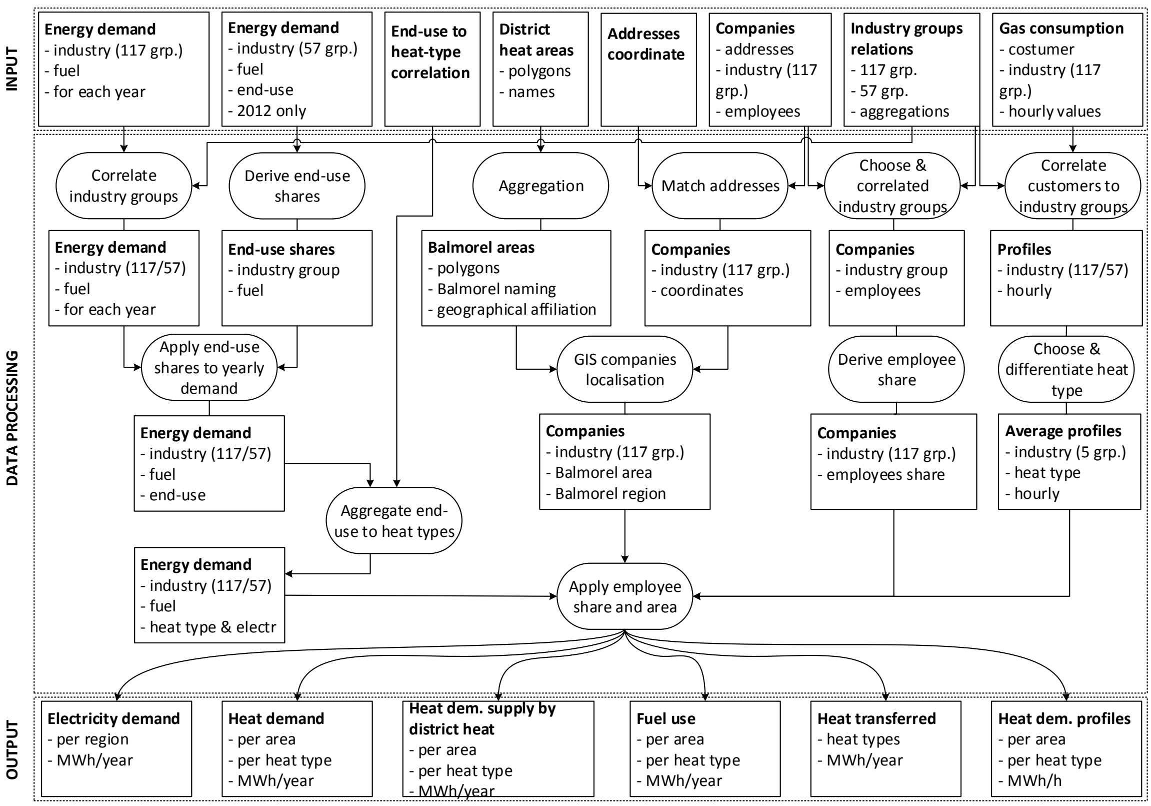

Figure 10.2: Data processing from original sources to input for Balmorel.

With the intention of unifying data from different sources, we used the details provided in Sørensen and Petersen (2015) from the year 2012 to link more recent data (Statistics Denmark, 2017). The first study provides detailed figures on end-use for 57 sectors, based

[1]Statistical classification of economic activities in the European Community.

on 22 end-use processes and 20 type of fuels, for the year 2012. On the other hand, Statistics Denmark only provides data about energy use by fuel and industry group for more recent years. To unify the sources and provide details for recent years (e.g. 2015 or 2016), we calculate a "end-use factor" from the relative share of fuel consumption by end-use for each industry group in the year 2012. Afterwards, we apply the "relative end-use factor" to more recent data from Statistics Denmark. As the format of the industry groups and some fuel naming conventions slightly differ in the two sources, these have to be correlated and aligned. The coupling of these data is one of the required data processing steps illustrated in Figure 10.2, which also reports the whole data processing flow for the study.

Another relevant step in the data handling regards the task of linking the location of industrial demand with excess heat sources and district heating networks, according to the geography of the energy system model. To this end, we perform a geo-location of: (i) the three types of heat demand (space, low temperature and high temperature), (ii) the industrial electricity demand and (iii) heat supply potential from a district heating (DH) network for industrial heat demand.

The geographical boundaries used for mapping the industrial energy consumption follow the logic of Balmorel and differ between heat and electricity. For electricity, the model considers "regional boundaries", meaning that all electricity demand in one region is grouped together. For Denmark, the model considers two regions (Denmark East and Denmark West), where the first includes the island of Zealand and the second includes Jutland and the island of Funen. On the other hand, the heat demands are linked with the district heating networks, as district heating is the most used source for the "space heating" end-use demand (See Section 10.4.2). Following Petrovic and Karlsson (2014), we consider 36 areas as an aggregation of the Danish district heating networks (Agency for Data Supply and Efficiency, 2018), publicly available as shape-files (Erhvervsstyrelsen, 2018). Other small-scale networks in rural areas are aggregated in two fictional DH areas for the eastern and western part of Denmark. To locate the industries with DH networks, we use the list of companies located in Denmark, which includes addresses, affiliation to detailed industry group and number of employees information (Virk, 2017). The geographic coordinates of the companies are derived by matching the addresses to an address list containing coordinates (Agency for Data Supply and Efficiency, 2017) using Python. Via the coordinate information, the companies are assigned to the 36 areas with a "spatial join operation" with the QGIS software (QGIS, 2017).

Once the industries are assigned to an area, the next task is to link the total industrial energy consumption with the unique industry. The method to locate the industrial energy demand by fuel and end-use is based on the employee shares per industrial groups (i.e. MWh/year per employee), a method already used in previous studies (Buhler et al., 2017). One recurrent issue in the method is that the number of employees is usually not proportional to the energy used, if considering companies from different industry groups. Meaning that an energy intensive group like service will have more employees per MWh/year than a production facility with high automation. However, the higher the level of details in the distinction between industry groups, the more similar the employee/energy ratio of the companies within the respective industry group. Considering the 57 industry groups used, the level of detail is sufficient to assume the number of employees to be proportional with the energy use in the respective industry group. As Figure 10.2 illustrates we calculate, for each company, the share of employees in relation to the sum of employees in the respective industry group. Subsequently, the yearly energy demand by fuel and end-use for each industry group is distributed to the companies according to the employee share. Based on the geo-location of the industries within an area, we obtain the process heat demand by fuel and end-use for each area and we locate the potential for heat supply from a DH network according to the three temperature levels defined. The industrial regional electricity demand is calculated with the same method.

10.4 Case study: Characteristics of the Danish industry sector

Relevant features characterising the industry sector range from sectoral classification to specific aspects about energy use, geo-location of consumption and potentials for fossil fuel reduction. As the intention is to provide a case description and a method that can be replicated for different study cases, open source data are used almost entirely throughout the study; confidential data are presented in aggregated form. To this end, we consider Denmark as a case study. The description of details characterising the Danish case constitutes the bases for the case study: with an overview about end-use processes, related fuel consumption and temporal profiles of consumption, the industry sector can be conveniently integrated in an energy system model according to the method proposed.

10.4.1 Structure of the Danish Industry

In the literature, industry is the term that refers to a variety of processes characterised by high energy intensity and use. As the term does not have a standard definition, the processes considered to represent the industrial sector vary from study to study, making similar analyses on the field difficult to compare. Buhler et al. (2016) shows that results derived from a broader approach provide additional insights and a stronger reliability, compared to other studies which considered a restricted number of processes and industries when assessing energy consumption (e.g. in the U.S. (Al-Ghandoor et al., 2010) or in Iran (Sanaei et al., 2012)). To this end, in this study we include agriculture, manufacturing and services in the term *industry* and *industry sector*. On the other hand, we exclude from the analysis transportation, both as branch and as end-use within the industry sector; hence, any energy use or emission balance related with transportation of industry feedstock and products is not part of the study.

Sørensen and Petersen (2015) proposes a data analysis about energy use in Danish industry, providing indications about the yearly energy demand in 2012 for 57 different sectors (excluding refinery, public service and construction), according to 20 fuel types and 22 end-uses. Details about the distribution of fuels amongst the end-uses are also provided.

To deal with the heterogeneity of the industry sector and to ease the illustration of the data available, in this case study we cluster the 57 industrial sectors in five groups according to similarities in temporal pattern of energy consumption: agriculture, production single shift, production double shift, production triple shift and services. The underlying assumptions behind the classification are based on Wiese and Baldini (2017), while the detailed classification of production industry groups can be found in the supplementary material.

The temporal pattern of energy consumption is different for each of the five categories. The consumption in agriculture, including gardening and horticulture, follows a pattern linked to seasonal activities, with lower energy use during summer and higher during fall and winter. Throughout the week, the consumption is higher during the day (working hours from 6 to 18) and week days and lower by night and in the weekend.

For services, the energy consumption is higher during daytime and weekdays, and lower during the nights and weekend, representing activities mostly conducted during normal working hours. The energy consumption is mostly constant throughout the year, apart from energy for space heating purposes that follows a seasonal pattern.

The production group includes manufacturing and extraction processes. The subdivision in single, double and triple shift is linked to the weekly schedule of activities. Single shift facilities typically operate during normal average working hours in the week days (e.g. 8-17) and are closed during weekends/holidays; double shift have longer operating hours (about 15 hours a day), they close during night and often during weekends/holidays; triple shift facilities run as continuous production (i.e. almost constant consumption throughout the year) and close down only few times a year. Sectors belonging to this group often present a steady base-load consumption for processes as auxiliaries or ovens.

10.4.2 Energy in the Danish industry

Figure 10.3 illustrates the total energy use for the Danish industry sector, gathered according to groups proposed, for the year 2012. The industry's energy use accounts for ∼156 PJ, distributed among production (∼88 PJ), service (∼48 PJ) and agriculture (∼19 PJ). In the production sector, double (50%) and triple shift (44%) cover a significant higher share compared to the single shift group (6%).

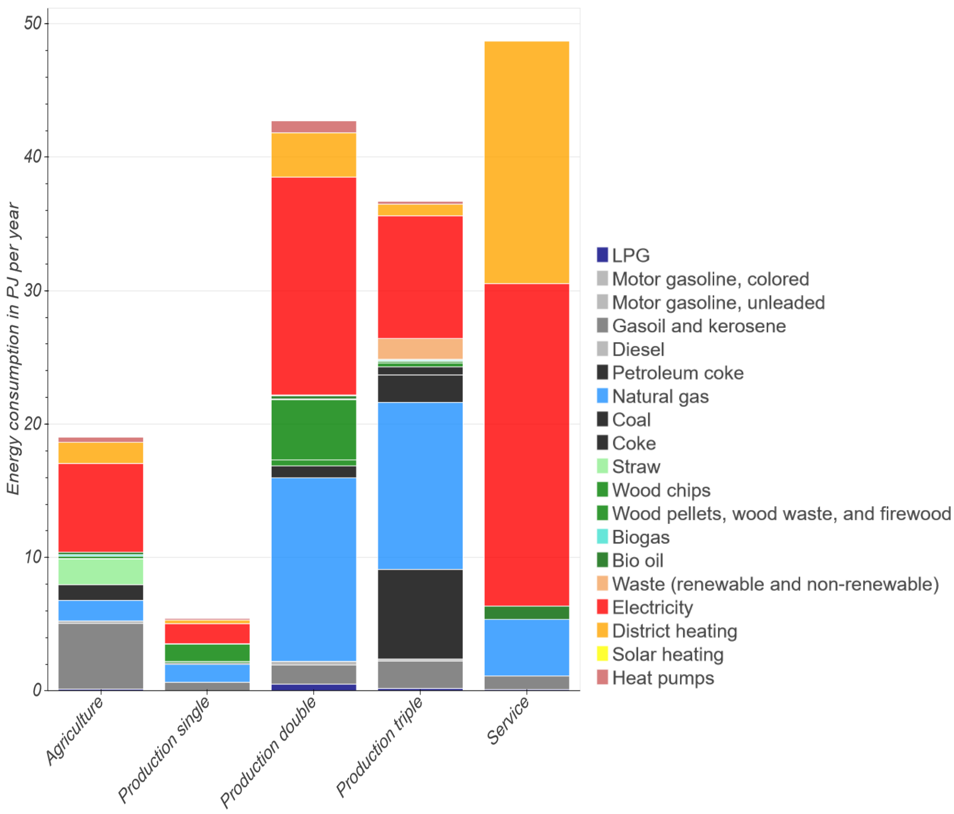

Figure 10.3: Total energy use for the Danish industry sector, excluding transport, by fuel (Sørensen and Petersen, 2015).

The fuel consumption is distributed unevenly among the sectors, with electricity (36%), natural gas (21%), district heating (15%), gasoil/kerosene (6.4%) and petroleum coke (4%) covering the majority of the consumption, while the other fuels contribute to a minor extent.

Figure 10.4, Figure 10.5 and Figure 10.6 show how, within the sectors, the fuels are used for different end-uses.

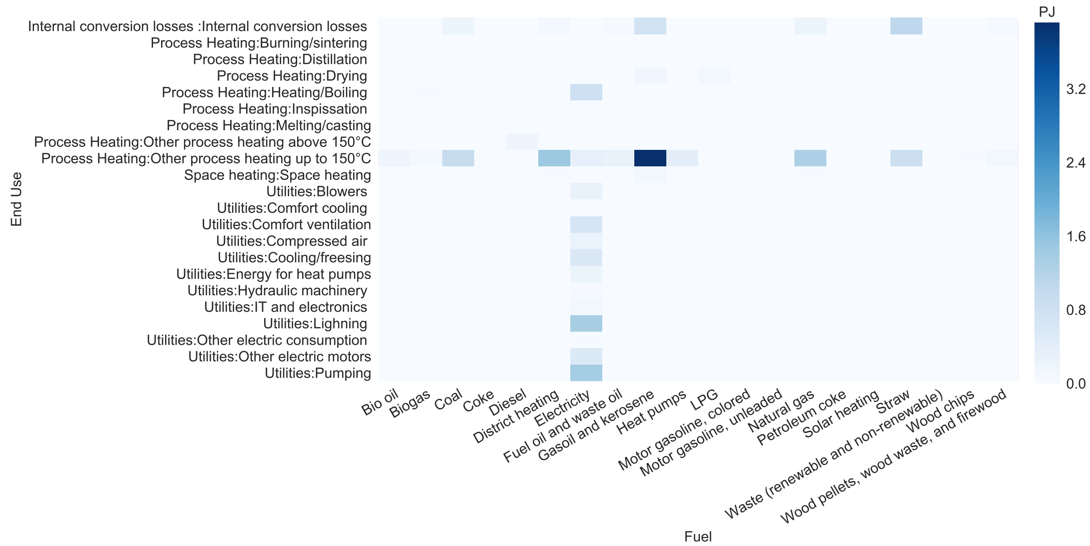

Figure 10.4: Breakdown of energy consumption by end-use and fuel in agriculture (Sørensen and Petersen, 2015).

The heat maps, presented in three clustered groups, provide an indication on the most energy-intensive processes in connection with the most employed fuels. In agriculture, most of the fuel consumption is related to processes heating up to 150°C (51%). Although the category includes different temperature levels of heat demands, most of the consumption is related with warming greenhouses for horticulture purposes. The temperature required for such uses is around 20-25°C (Johansson and Rizzo, 2008), so heat from district heating networks can be used as a direct input, as the supply temperatures from district heating networks are in the range of 70-90°C.

Figure 10.5: Breakdown of energy consumption by end-use and fuel in production (Sørensen and Petersen, 2015).

In the production sector, processes such as drying (15%), heating/boiling (16%) and space heating (11%) are predominant, while in service, space heating (50%) and lightning (17%) together consume more than half of the total fuels.

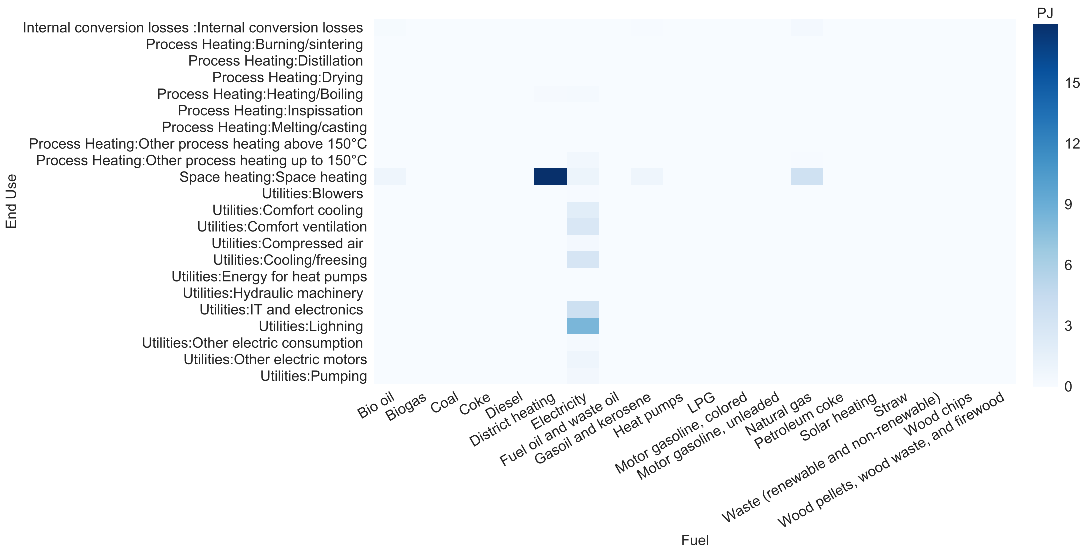

Figure 10.6: Breakdown of energy consumption by end-use and fuel in services (Sørensen and Petersen, 2015).

Regarding the fuel use, the production sector presents a high diversity of fuels employed for various end-uses, with natural gas and electricity (31% each) standing out. Electricity (50%) and district heating (37%) dominate the total energy use in the service sector, while electricity (34%) and gasoil/kerosene (25%) are predominant in agriculture.

10.4.2.1 Energy use by industry groups and fuels

Based on the data processing presented in the methodology, Table 10.2 shows the resulting values for years subsequent to 2012. The values highlight a drop in the total fuel use to ∼148 PJ in 2014, followed by a raise to ∼152 PJ and ∼154 PJ in 2015 and 2016. Analysing the macro changes for the industry groups during the period 2012-2016 reported in Table 10.2, one can notice that the energy use in agriculture does not change significantly. Service, after a decrease until 2014, increased again until 2016, almost to similar levels as 2012 (∼ 48 PJ). For production, the single and double shift group present a pattern similar to service, with double shift group eventually having greater consumption in 2016 compared to 2012 levels. Triple shift group presents a more stable trend around ∼ 37 PJ.

Table 10.2: Sum of fuel consumption [PJ] in the aggregated industry groups for different years. Own calculations based on Statistics Denmark (2017).

Industry group	2012	2013	2014	2015	2016
Agriculture	19.3	19.4	18.4	18.6	18.5
Service	52.3	49.9	46.4	47.6	49.7
Production single shift	5.1	4.8	4.6	5.6	4.9
Production double shift	42.8	41.7	41.3	42.6	43.2
Production triple shift	38.6	37.0	37.7	37.9	38.1
Total	158.1	152.8	148.4	152.3	154.4

10.4.2.2 Heat levels

According to the heat classification proposed in the methodology, Table 10.3 presents the end-uses according to temperature levels of the heat demand: space heat, process heat low and process heat high temperature.

Table 10.3: Clustering end-use by heat level. Process heat levels from Sørensen and Petersen (2015)

End-use	Temperature level [°C]	Model heat type
Space heating	50-90	space heat
Distillation	50-100	process low
Heating/Boiling	70-110	process low
Drying	~ 100	process low
Inspissation	130	process low
Burning/Sintering	≥ 250	process high
Melting/Casting	≥ 300	process high

Once again, according to the methods proposed, we use the relative end-use shares from 2012 (Sørensen and Petersen, 2015) to link more recent data sources and calculate the end-use fuel consumption for 2013-2016 based on the yearly data on fuel use by industry group (Statistics Denmark, 2017). Table 10.4 displays the trends of consumption by end-use, for the period 2012-2016.

10.4.2.3 Consumption profiles

Details about temporal variations of industrial electricity and heat consumption are necessary, while investigating the impact of changes in consumption on a system wide scale. The aggregated industry groups introduced (agriculture, service, production single, dou-

Table 10.4: Sum of fuel consumption [PJ] by end-use in the aggregated industry groups for different years. Own calculations based on Sørensen and Petersen (2015); Statistics Denmark (2017).

End-use	2012	2013	2014	2015	2016
Electricity	52.0	51.6	52.9	54	52.1
Heat Pump	0.6	0.7	0.7	0.7	0.6
Losses	8.1	7.5	6.8	7	7.3
Process Heat High	12.6	12.4	13.1	13.2	13.6
Process Heat Low	47.3	44.4	42.8	43.5	44.6
Space Heat	37.5	36.2	32.1	33.9	36.2
Total	158.1	152.8	148.4	152.3	154.4

ble, triple shift) are characterised by different temporal patterns. Furthermore, temporal profile of consumption differ significantly according to the purpose: fuel consumption for process heat and electricity are process dependent, while fuel consumption for space heat is linked to a strong seasonal pattern. Relevant considerations about these insights are also discussed in Wiese and Baldini (2017)[2].

As Figure 10.5 and other studies show that natural gas is the most employed fuel for process-heat purposes in Danish industry (Wiese and Baldini, 2017), in this study we use temporal patterns of natural gas consumption, for the year 2016, to derive the heat demand profiles for space and process heat consumption (Dansk Gas Distribution, 2016). Due to confidentiality, we present the profiles aggregated according to the categorisation proposed. Sectoral profiles of hourly electricity consumption are collected from Andersen et al. (2013a) and Andersen et al. (2013b).

Electricity Figure 10.7 and Figure 10.8 present details about temporal pattern of electricity consumption on a yearly scale.

Figure 10.7 presents the profiles in terms of boxplots, where the size of each box relate with the range of variation in the profiles: the larger the box, the larger the yearly variation. The biggest range of variations within the profiles occurs for agriculture and production single shift, highlighting a seasonal consumption profile related to farming activities for the former and a considerable variation in weekdays, weekends and holidays activities for the latter. For the production category, the size of the boxplots decreases in size for higher number of production shifts (i.e. the triple shift shows the smallest box) suggesting

[2] To exemplify the understanding of the work performed with the temporal profiles of consumption, we report an extract from the 12^{th} SDEWES 17 Conference proceeding in Appendix 10.6. Please note that the sections reported in the Appendix are not part of the official publication in the Journal of Cleaner Production.

a lower range of variation of the profiles for these categories.

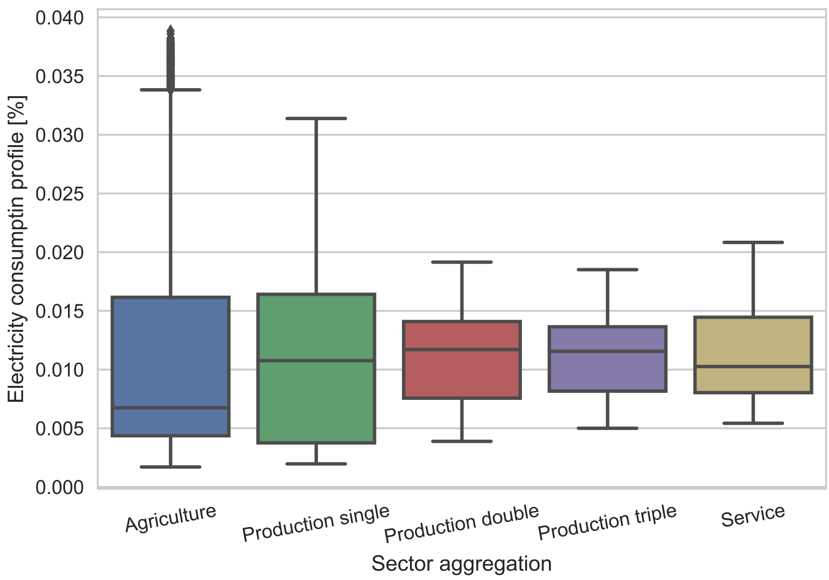

Figure 10.7: Boxplots of relative electricity consumption. Own calculations based on Energinet.dk (2017); NordPoolSpot (2018); Elforbrugs Panelerne (2018); Andersen et al. (2013a); Andersen et al. (2013b); Sørensen and Petersen (2015).

Figure 10.8 shows the development of the temporal patterns of electricity consumption throughout the year. The greatest seasonal variation occurs for agriculture.

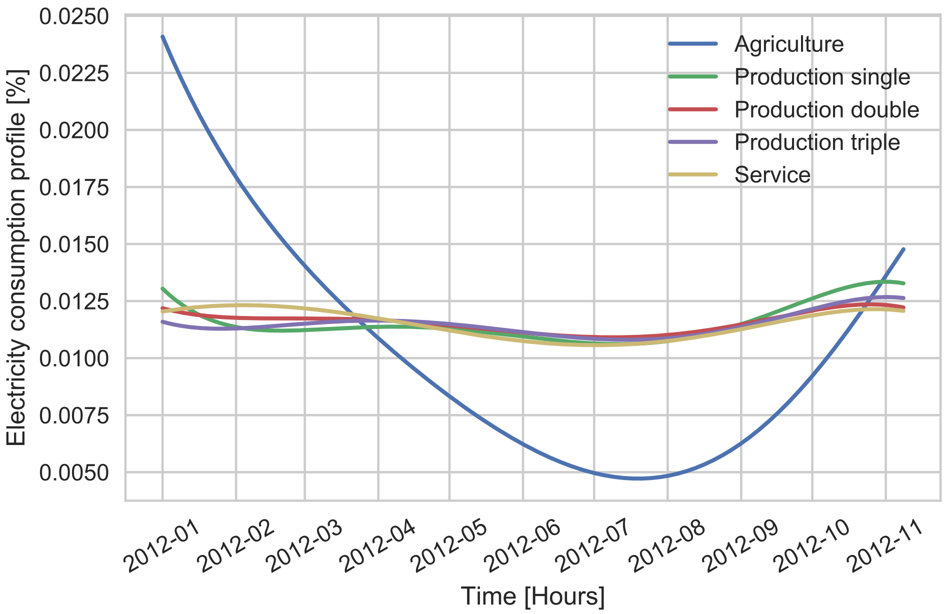

Figure 10.8: Relative variation of seasonal electricity consumption, trend-lines (fit to the 18th order). Own calculations based on Energinet.dk (2017); NordPoolSpot (2018); Elforbrugs Panelerne (2018); Andersen et al. (2013a); Andersen et al. (2013b); Sørensen and Petersen (2015).

Moreover, service, production single and double shift present a decreased consumption in correspondence with summer holidays, while production triple shift shows a rather constant profile during the year.

Fuel consumption for space heat purpose The profiles in Figure 10.9 and Figure 10.10 show the fuel consumption for space heat purpose in industry, on a yearly and a weekly scale. Figure 10.9 gives an indication of the seasonal variation, with a higher consumption by fall and winter, compared to spring and summer levels. Some drops occur during the year, probably related with changes in weather conditions that required a lower use of fuels for space heating. Although following similar trends, the profiles differ from each other. The triple shift production stands out during the summer with higher levels of consumption compared to other categories, exception made for August. A

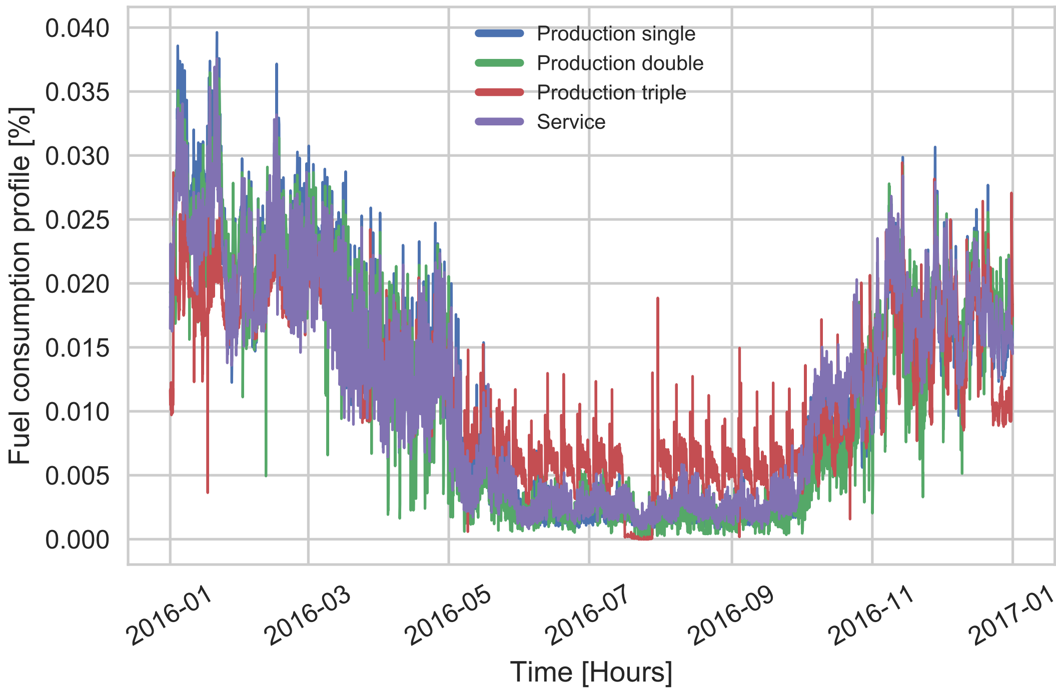

Figure 10.9: Hourly profile of fuel consumption for space heat purposes in one year. Own calculations based on Dansk Gas Distribution (2016); Sørensen and Petersen (2015).

similar trend is highlighted in Figure 10.10, which shows that, on weekly basis, the triple shift production group has the smallest variation, indicating a range of processes with a continuous consumption.

Fuel consumption for process heat purpose The yearly profiles of fuel consumption for process heat purposes in Figure 10.11 highlight the relevant impact of holidays on the demand, as the consumption is significantly lower during holidays such as Easter, summer and Christmas.

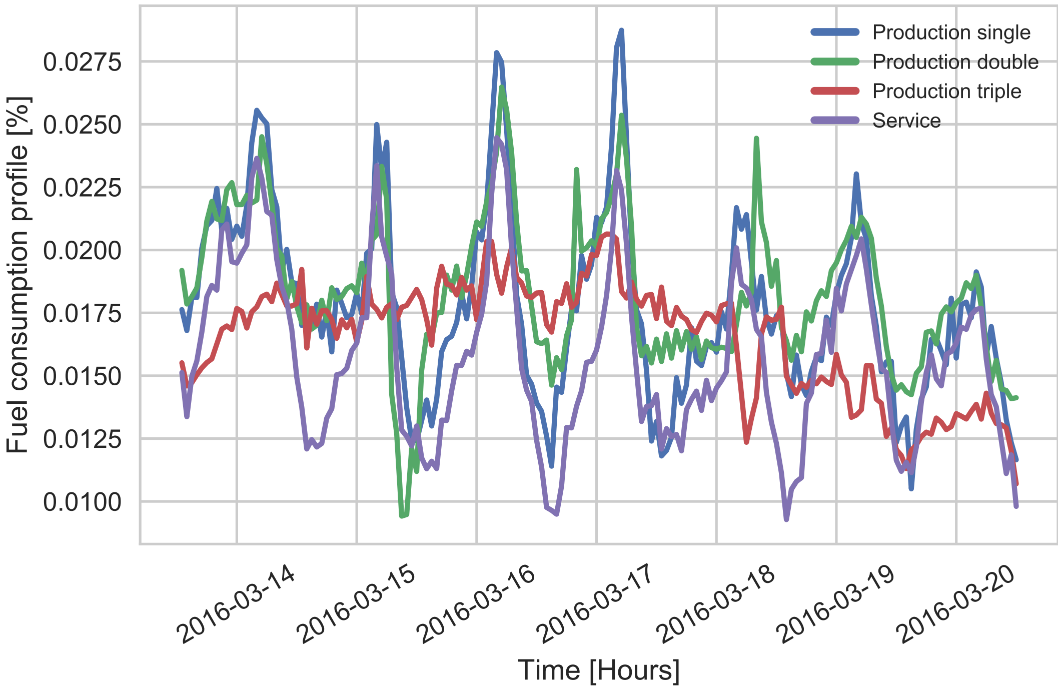

Figure 10.10: Hourly profile of fuel consumption for space heat purposes in one week. Own calculations based on Dansk Gas Distribution (2016); Sørensen and Petersen (2015).

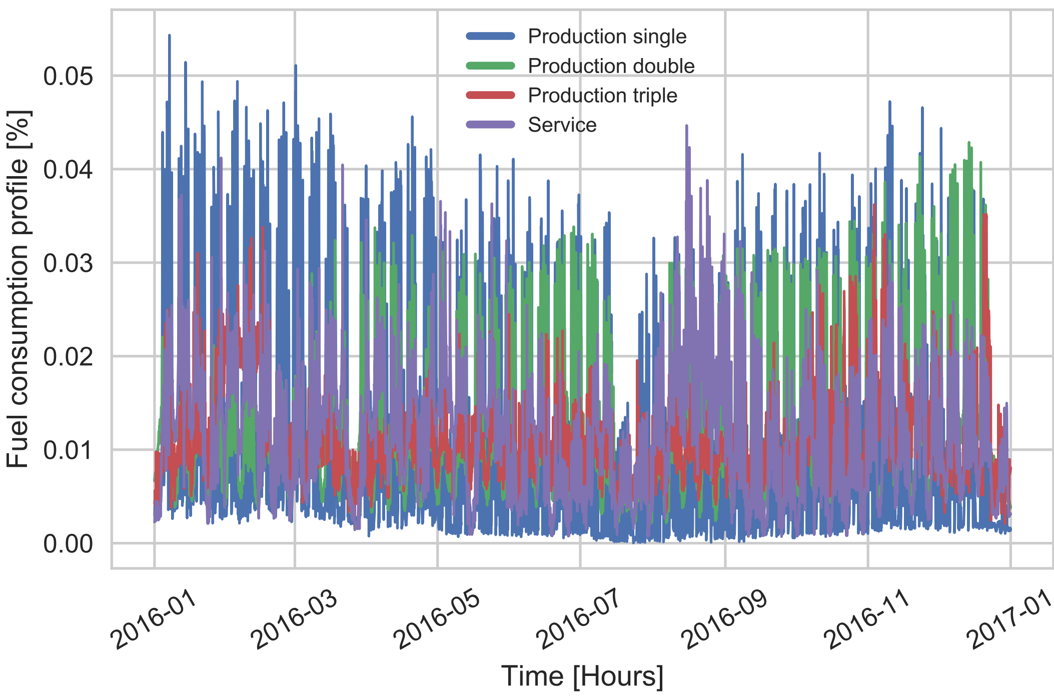

Figure 10.11: Hourly profile of fuel consumption for process heat purposes in one year. Own calculations based on Dansk Gas Distribution (2016); Sørensen and Petersen (2015).

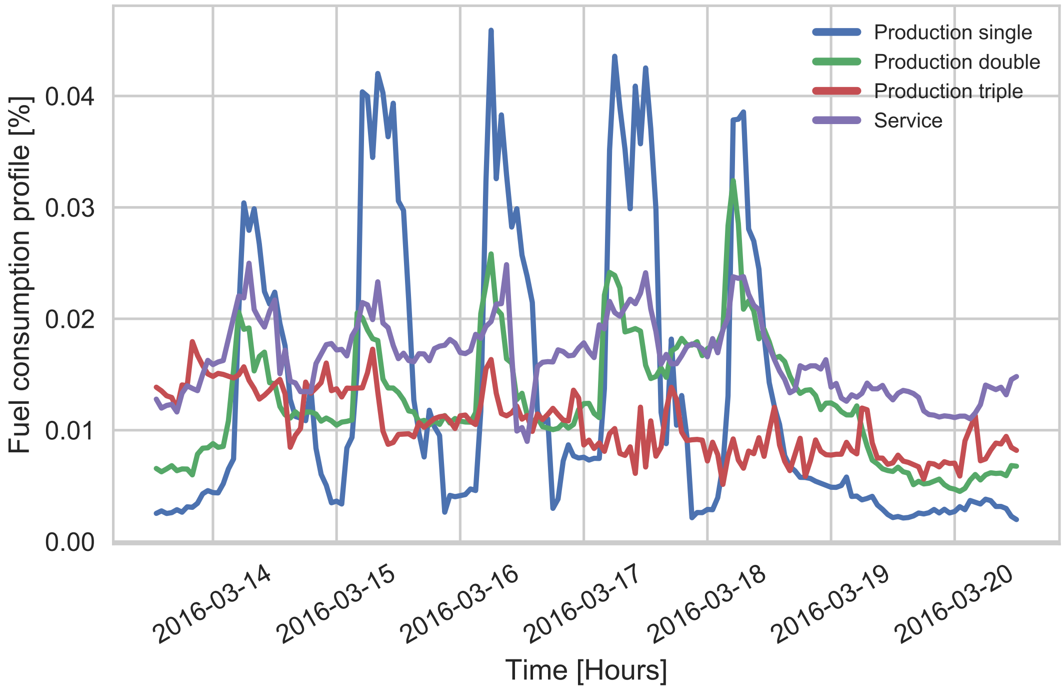

Figure 10.12: Hourly profile of fuel consumption for process heat purposes in one week. Own calculations based on Dansk Gas Distribution (2016); Sørensen and Petersen (2015); Wiese and Baldini (2017). The division the sectoral groups is based on Wiese and Baldini (2017) while the division into share of end-use of fuel on Sørensen and Petersen (2015).

Differently from fuel consumption for space heating, the profiles show the link with the working schedule, with a clear weekly variation in the consumption throughout the year. Also, exception made for the holidays, production single shift shows the largest variation, while the triple shift category the smallest. Figure 10.12 confirm the trend on a weekly scale, highlighting that processes of triple shift barely reduce their energy consumption in the week ends, making them a potential candidates for interventions of fossil fuel reduction.

10.4.2.4 Geographical mapping of industrial energy consumption

In a context of interrelation between commodities (e.g. heat sources, district heating networks, combined heat and power production) and particularly for cases of potential applicability of energy cascading (i.e. re-utilisation of excess heat for different purposes), it is essential to consider the geographical location of industrial energy demand. In the case of Denmark, district heating plays a major role, with approximately 60% of the Danish heating demand supplied via district heat networks and 40% of fuel used for DH purposes based on renewable sources (Münster et al., 2012). An increased use of district heat for space heat purposes - linked with an higher share of renewable sources as primary input in the production - represents a relevant option to reduce the use of fossil fuel in the future industry. The feasibility of this option depends on the location of the industrial demand as, intuitively, the heat source can be used by an industry only if it is on the proximity of a district heating area. As highlighted in the methodology, similar considerations applies for energy cascading cases such as: (i) using district heat for process heat purposes in heat pumps to boost the quality of the heat and adapt it to the temperature needed (Buhler et al., 2016) or (ii) using excess heat from industrial processes in district heating networks.

According to the approach proposed in Section 10.3.4, we locate the potential for heat supply from a DH network according to the three temperature levels defined. The resulting space heat demand within district heat areas sums up to ∼17 PJ of which ∼11 PJ are already supplied by district heat; ∼16 PJ of space heat demand were found to be located out of existing district heat areas. Figure 10.13 illustrates the share of space heat demand supplied by district heat for the 36 areas considered. The share per area ranges from 40 to 80%.

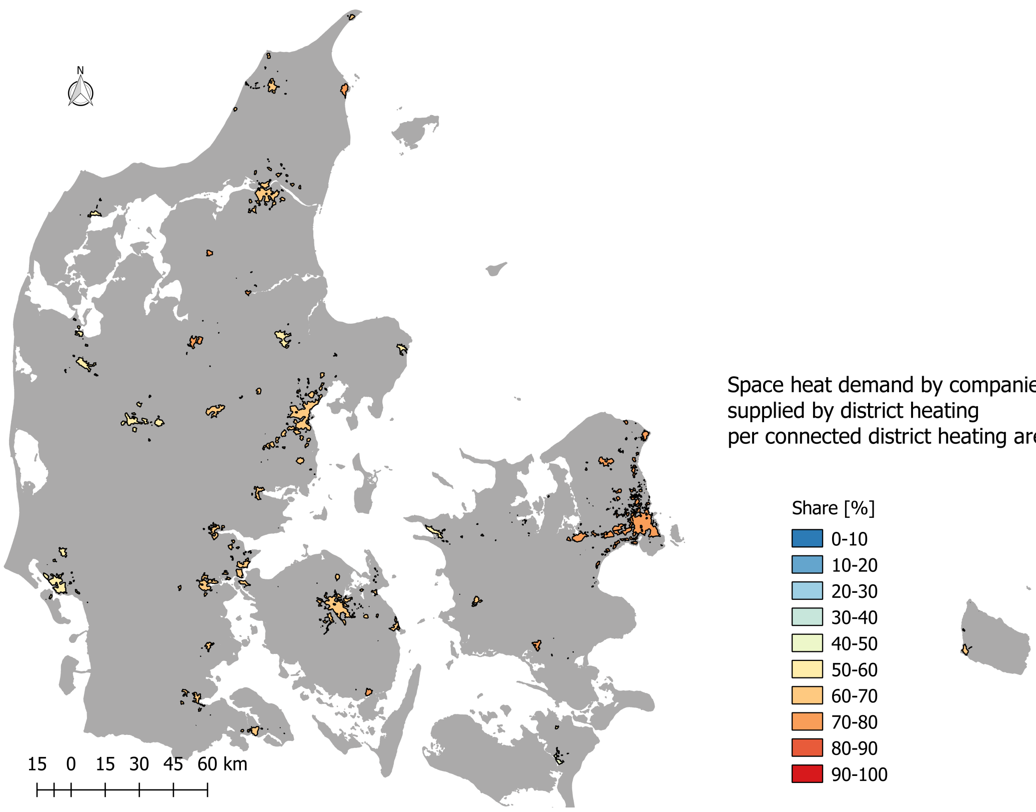

Figure 10.13: Share of space heat demand of companies supplied by district heat. Own calculations based on Agency for Data Supply and Efficiency (2018); Virk (2017); Buhler et al. (2018a); Petrovic and Karlsson (2014); Sørensen and Petersen (2015); Statistics Denmark (2017).

Regarding process heat at low temperature, about 10 PJ are located within district heat areas and ~33 PJ outside. Of this total, the share already supplied by district heat ranges between 0 and 30% for the different areas, as Figure 10.14 shows.

For process heat at high temperature, the analysis indicates that about 3 PJ are located within the current district heat areas, while ~10 PJ are located outside; a possible source of excess heat that could be used for district heating purposes.

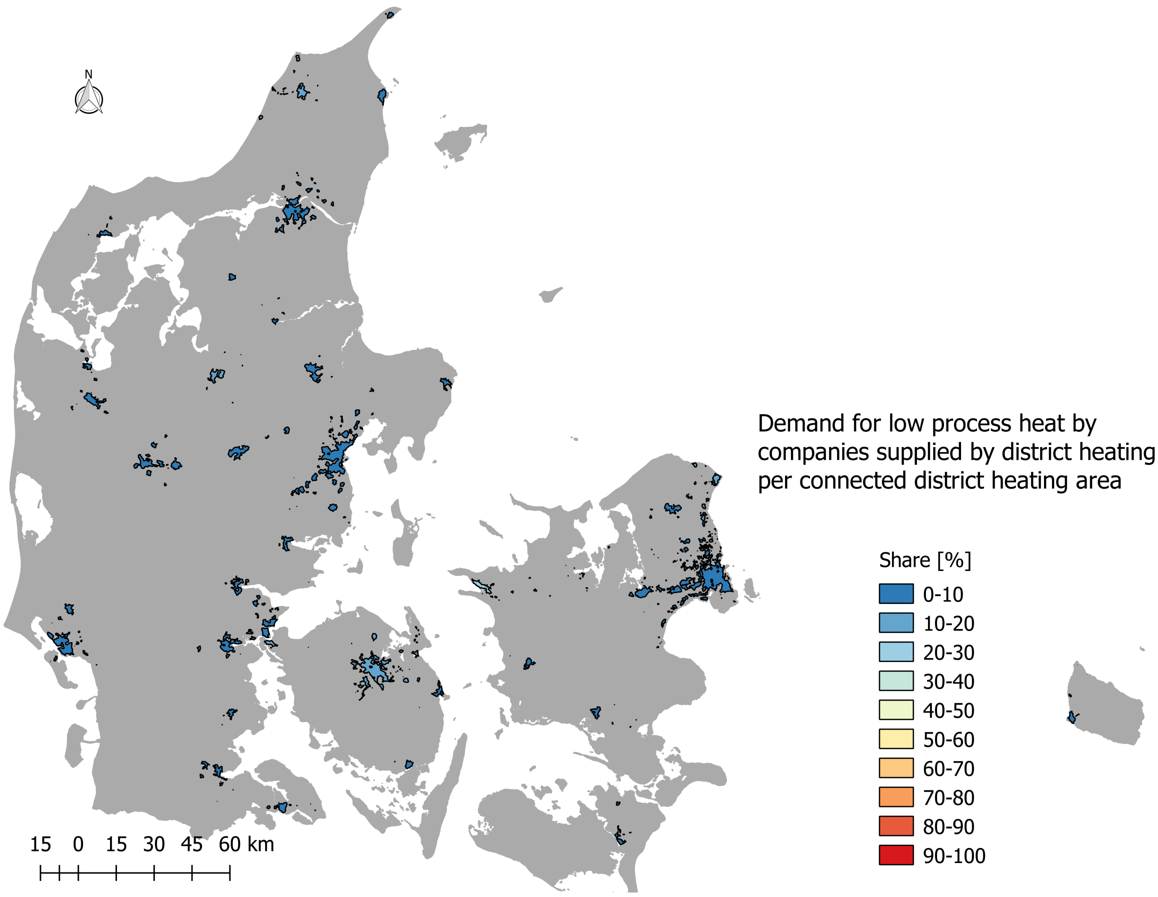

Figure 10.14: Share of low process heat demand supplied by district heat. Own calculations based on Agency for Data Supply and Efficiency (2018); Virk (2017); Buhler et al. (2018a); Petrovic and Karlsson (2014); Sørensen and Petersen (2015); Statistics Denmark (2017).

10.4.3 Potentials for fossil fuel reduction options

In relation to the analysis of different end-uses and the insights on the geographical analysis, we summarise different fossil fuels reduction options in industry for electricity, space heat, process heat low and high temperature purposes. Table 10.5 proposes estimates and considerations for all industry groups, based on different sources.

According to energy audits performed in most of the Danish industries, the Danish Energy Agency (2015) reports that the potential for energy savings in industry amounts to about 39 PJ, with most of the savings being available for electricity (46%) and heat low temperature (39%) processes. The potential, reported for a maximum pay back time of 10 years, considers improvements in end-use processes, with cross-cutting technologies in process integration, electric motors and transmission and automation as main pillars. As end-uses vary in size and numbers across the industry types, the values are gathered by electricity and heat levels for the whole industry sector; in case of need, they can be tailored according to the level of details required, e.g. for different industry branches.

Table 10.5: Overview of fossil fuels reduction options for industrial purposes (sources are provided in the footnotes).

Category	Space heat	Process heat low	Proces heat high	Electricity
Energy savings [3]	5.2 [PJ/year]	15.6 [PJ/year]	0.4 [PJ/year]	18.3 [PJ/year]
Excess heat potential[4]	4.9 [PJ/year]	4.90 [PJ/year]	limited	NA
Electrification[5]	Heat pump(HP)	Electric heat; ~88% techn. convertible	Electric heat; ~25% techn. convertible	NA
Biomass DK[6]: 75-315 [PJ/year]	Applicable	Applicable	Limited	Main energy system
Biogas DK[7]: 35-170 [PJ/year]	Restricted by location; ~10 [€/GJ][8]	Restricted by location and application	NA	Main energy system
Renewable gas[9]	12-18 [€/GJ]	12-18 [€/GJ]	12-18 [€/GJ]	Decided on system level

[3] Danish Energy Agency (2015)
[4] Buhler et al. (2017); Buhler et al. (2018a)
[5] Danish Energy Agency (2014b); Danish Gas Technology Center (2013a)
[6] EA Energy Analysis and University of Southern Denmark (2016)
[7] EA Energy Analysis and University of Southern Denmark (2016)
[8] Jensen and Skovsgaard (2017)
[9] Ea Energy Analysis (2017); Jensen and Skovsgaard (2017)

Regarding excess heat potentials, recent studies on a Danish context conclude that 8.5 PJ of accessible industrial excess heat could supply up to 4.9 PJ of the current district heat demand each year (Buhler et al., 2017). Of this amount, only 36% of the excess heat would require a heat pump to raise the temperature for district heating purposes (∼70-80°C). Similar studies, about spatio-temporal and economic analysis of industrial excess heat (Buhler et al., 2018a) and GIS-based case studies on excess heat (Buhler et al., 2018b), also report details about excess heat by district heat area, temperature range and industry group, highlighting a potential of 4.9 PJ for process heat low temperature purposes, using heat pumps to boost the heat temperatures. Similar considerations do not pertain high temperature processes, as the amount of energy consumption necessary to elevate the quality of heat from district heat levels to the required temperatures, would make the case non convenient.

On the premises of an energy system highly based on renewable production, electrification is also a viable option to reduce fossil fuel use for all three process heat categories. For the case of Denmark, the Danish Energy Agency (2014b) and the Danish Gas Technology Center (2013a) assess the share of electrification potential for different processes and technology types, suggesting 88% for process low temperature, and 25% for process high temperature.

The application for space heat and for low heat temperature processes imply the use of heat pumps as a complementary option, using ground or ambient temperature differences to generate heat. Preliminary indications show that a significant part of the industrial space heat can be supplied by heat pumps, as this technology has become commercially available and more economically convenient (Energinet.dk, 2015). Applied cases also show the practicality of using excess heat to this end, using heat pumps (Kortegaard Støchkel et al., 2017).

The case is different for processes at low temperature heat. Supply of process heat of up to 150°C from either excess heat or district heat in combination with a heat pump is technical possible, but the economic feasibility highly depends on the supply and the demand temperature; the higher the difference, the lower the coefficient of performance (COP) and thus the higher the required electricity share. Also, generally electrification is straightforward for processes requiring heat radiation, however there are exceptions. For processes highly based on gas use (e.g. in slaughterhouses, production of oil, fat, milk products, thickening substances like pektin), direct change to electricity is not as straightforward as for radiation. According to industrial facilities, a more detailed analysis of the circumstances and the temperatures would be required to define the applicability for each case (Danish Gas Technology Center, 2013a).

Electrification for process heat high temperature, using heat pumps, is more challenging as, due to the high temperatures required, heat pumps are not suitable tools for the task. For this category, some processes are thus directly electrified. The low rate of conversion for process heat high temperature is also related with processes requiring flames (e.g. glass fibre production) that cannot be directly electrified, exception made for some few processes where electricity could potentially substitute the flames (e.g. where the heat is transferred by radiation and the flue gas does not directly get in contact with the process material).

Regarding biomass, a meta-study concludes that the potential for biomass in Denmark ranges between 75-315 PJ/year (EA Energy Analysis and University of Southern Denmark, 2016). Biomass can be used as a fuel to power various processes generating heat at different temperatures. However, the applicability for high temperature processes is limited, as the low heating value of the biomass would require a higher amount of fuel input, compared to other sources.

Biomass and electricity could in total replace up to 78-85 % of the current natural gas use in industry. For most appliances, the costs for the biomass option seems to be higher than electrification, even when including electricity grid connection or enforcement costs (Danish Gas Technology Center, 2013b).

Solid or liquid organic resources can also be used as a source to derive biogas, with a potential applicability about 35-170 PJ/year (EA Energy Analysis and University of Southern Denmark, 2016). However, as other sectors than industry will require biomass and biogas for various uses, the price of these commodities might increase. Additionally, the use of most of these bio-based commodities is restricted regionally, due to the high transport costs that some kinds of biomass require (e.g. manure).

Raw biogas represents another opportunity to replace highly carbon based fuels for industry purposes. Although it cannot be used directly in most of the existing gas appliances due to its composition, it can be converted to similar fuels, as the main composition (methane and CO_2) is similar to natural gas. For example, raw biogas from anaerobic digestion or thermal gasification can be upgraded by removing the CO_2; otherwise the CO_2-component can be transformed to methane, adding hydrogen. Biogas can then be used for appliances currently using natural gas, reducing significantly the CO_2 emissions. Studies on thermal gasification in the Danish energy system (Ea Energy Analysis, 2017) and on the impact of CO2-costs on biogas usage (Jensen and Skovsgaard, 2017) estimate the biomass price around 12-18 €/GJ.

10.5 Discussion

In the context of assessing the role of industry in the future energy system, the study first develops a conceptual model for the industry sector in an integrated energy system model and then presents a description of the specific aspects of industrial consumption, in terms of end-uses input fuels, temporal profiles of energy consumption and options to reduce fossil fuels use.

The conceptual model for the industry sector is developed in the framework of an integrated energy system model, providing a tool that can be used as benchmark to test the impact of fossil-fuel reduction options on a system wide scale. The introduction of a high level of detail allows tailored analyses, such as resilience of future configuration of energy system when the industry will electrify part of its processes. Also, the details provided about the sectoral fuel consumption facilitate the investigation on the potential (application and effect) for fossil fuel reduction in future configuration of the industry sector, given the upcoming targets of fossil fuel reduction policies. The modelling of the fossil fuel reduction options, integrated within the model proposed, can lead to considerations about the qualitative and quantitative configuration for a system transformation, allowing the measures to compete on economic (Eqs.(10.1)-(10.10)) and environmental terms (Eq.(10.19)). To this end, elements such as generation mix in the electricity and heat supply, electricity prices and future targets are decisive. Eq.(10.15) can provide considerations about the contribution of each heat process technology in the future of industry, as well as the role of heat pumps, which are expected to take over in different end-uses.

The methodology developed can be applied to investigate tailored research questions, exploiting the simultaneous optimisation of power, district heat and industry dispatches and characteristics. Among other, the model can investigate on the role of biomass and biogass for sectors and end-uses, on the convenient use of renewable gasses, on the uptake of electrification in the long run considering renewable based energy systems and on the flexibility that electrified industrial heat and electricity demand could provide to the rest of the system.

The theoretical approach proposed can be potentially used for other case studies, particularly for countries that share a similar structure in terms of energy system (e.g. high share of district heat and possibility for energy cascading). Furthermore, as the energy system model Balmorel considers a set of different countries (e.g. Germany, Finland, Sweden, Norway), a similar analysis of the industrial sector can be performed in any of those countries with the same model, given data availability. The applied case of Denmark is selected because of intensive data availability. On European level, Eurostat provides data on fuel usage and emission by sector, which are more aggregated than the presented

Danish data, but could be nonetheless used for the modelling approach described in the study (Eurostat, 2017a). Open source data about fuel use by end-use in industry, as well as geographical level of detail about addresses and company locations, are more difficult to retrieve elsewhere. Being aware of the difficulties to gather industrial data, throughout the report we report details about the structure of the Danish sector and the various sources for the data, so that other analyses can similarly adapt the data sources for the need, emulating the study.

In relation to the modelling framework proposed, the investigation on the characteristics of the industry sector on the applied Danish case, has highlighted the following key points. Electricity, natural gas and district heating dominate the total industrial energy consumption, while the relevance of consumption by end-use varies according to the sector considered. Processes heating up to 150°C (51%) dominate in agriculture, space heating (50%) and lightning (17%) in service while the production sectors is more diversified, including drying (15%), heating/boiling (16%) and space heating (11%). This opens the bases for the possible transformation of the sector, as most of the end-uses, currently using fossil fuels, can be replaced with cleaner alternatives. In particular, heat pumps and energy cascading cover a relevant role, given the high share of heat demand of lower temperatures among the end-uses.

The temporal profiles presented stress the importance of using real data instead of constructed profiles, indicating situations that are particularly useful for studies on energy systems, such as drops in energy demand, seasonality of the profiles or weekly schedules. Given the rising share of fluctuating energy sources in energy systems, realistic temporal consumption patterns becomes necessary in energy modelling, particularly in relation to demand occurrence and related flexibility. In this context, electrification is particularly relevant given its existing potential (88% and 25% for low and high temperature processes) as it will enhance the industrial dependence from electricity use and, consequently, from the electricity generation sources of the energy system. Also, the analysis on the profiles highlights that process in the triple shift category are mostly constant throughout the year. Hence, interventions of fossil fuel reduction should target and prioritise these particular end-uses. Although the profiles are derived on the bases of data from different years, they are generally applicable for modelling the temporal variation of demand in the industry sector. In a short term horizon, it is likely that the absolute value of consumption slightly varies, but this should not affect the relative temporal development of the profiles, exception made for unforeseen events (e.g. country crisis, massive relocation of activities, etc.).

The process of mapping the industrial energy consumption shows the relevance of the high geographical resolution, particularly when dealing with interconnections between commodities (e.g. heat and electricity) and end-uses. The analysis indicates that 6 PJ of heat demand could be additionally supplied by district heat. For energy systems characterised by a high share of district heat, it is crucial to consider the proximity component between sources and consumers, as cases such as using excess heat in heat pumps for district heating and processes purpose can be relevant in the context of fossil fuel reduction in industry. These considerations might be less important for countries where district heat is not substantial, and would consequently reduce the requirements of geographical resolution of the input data.

The analysis of the options to reduce fossil fuels in industry has identified savings, energy cascading, electrification (heat pumps and direct electrification), biomass, biogas and renewable gas as viable options. In regard to process electrification, the potential applicability of heat pumps stands out as the most relevant option, because of its flexibility to combine the use of electricity to provide heat at different temperature levels. Given the importance and the interconnection within the energy system, it is paramount to distinguish technical properties and the coefficient of performance (COP) according on the application area when modelling heat pumps, as the performances are strictly dependent on the temperature levels. The fact that electrification is a viable option for space heat, process heat low, and even process heat high temperature strengthens the need to consider the industrial demand in relation to the rest of the electricity and heat system, combining temporal and geographical resolution, for an in-depth analysis of reducing fossil fuels in industry. Among the end-uses presented, space heat, low temperature and electricity based processes enjoy a widespread series of options to reduce their impact in terms of fossil fuels. In particular, savings and excess heat can potentially contribute up to 38 PJ and 9 PJ respectively. Biomass (75-315 PJ), biogas (35-170 PJ) and renewable gas, available with a greater potential, can also represent a great opportunity for fossil fuel reduction, although they are limited in the application due to technical limits (e.g. adaptability to natural gas processes), geographical restriction or competing demands for the scarce bioenergy in the future.

10.6 Conclusion

In the framework of assessing the transformation of the industry sector towards more sustainable alternatives, it is paramount to consider the elements characterising the industry sector. Given the interdependencies between industry sector and energy system, the adoption of fossil-fuel reduction measures can influence the operation and transformation of the energy system. Considering the current state of industry modelling in existing bottom-up energy system models, it is currently not possible to assess such implications.

Focusing on an applied study case for Denmark, the study proposes a method to simulate and optimise operational aspects of the industry sector at high level of details. By providing a detailed conceptual model considering structure of the processes with regard to input fuels, temporal profiles of energy consumption and options to reduce fossil fuels use, the paper narrows the knowledge gap on modelling and representation of the industrial sector in bottom-up energy system models.

Considerations sparking from the structural analysis of the industry show the potential applicability of energy cascading, electrification and fuel substitution for industrial processes targeting end-uses currently based on gas and other fuels. Engaging elements and technologies interlinked within the energy system such as heat pumps, are proposed as solutions for transforming the industry sector.

The integration of industry in an established energy system model, creates a benchmark for analyses that can focus simultaneously on the impact of changes in the industry and in the energy sector on a system wide scale. In this framework, the transformation of the energy use in industry sector can be simulated according to more stringent policies capping CO_2 emission levels and specific support schemes, paving the way for carbon neutral societies and a more sustainable, yet resilient, future energy system.

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Appendix

Appendix A. Supplementary data

Supplementary data related to this article can be found at **this repository**.

Appendix B. Energy Consumption Profiles

Methodology

The hourly resolution of energy demand and supply provides specific details about the flexible operation of energy generating technologies, transmission and use of energy. In energy systems with high shares of fluctuating renewables, electricity and heat demand have essential influence on the system operation and configuration. Since hourly energy consumption profiles are fundamental in an energy system model with an hourly temporal resolution, such energy consumption profiles have to reflect realistic patterns.

Electricity Electricity consumption profiles are often openly available only at a higher level of aggregation. The Danish transmission system operator Energinet.dk (Energinet.dk, 2017) and Nord Pool, the Nordic power market trading platform, provide such data on an hourly resolution at country and regional level (NordPoolSpot, 2016).

Based on those and other data sources (Elforbrugs Panelerne, 2018), Andersen et al. (2013a); Andersen et al. (2013b) developed a methodology to generate industry-sector related electricity consumption profiles (percentage load profiles). This data covers approximately more than half of the electricity consumption profiles of the 57 industrial sectors considered and are utilised in this study.

These profiles are grouped according to the main five categories (agriculture, service, production single, double, triple) to enable an easier comparison on consumption patterns in the same group. The consumption profiles for the remaining sectors (i.e. the ones without a profile) are then derived through three steps:

1. given a sector (e.g. gardening) with a missing profile, we first check to which main category it belongs (in this case agriculture);

2. the selected sector is then compared to the characteristics of the other sectors (for which profiles are available) in the same category in terms of: fuel consumption, end-uses and qualitative characteristics about the pattern (e.g. seasonal trends);

3. the profile of the missing sector is set to be the same as the profile, in the same category, which share similar characteristics.

The process allows to estimate consumption patterns for all the 57 sectors. The relative profiles are then associated with the absolute value of consumption to determine the hourly load profiles in absolute values (MWh). The resulting electricity profiles are thereafter checked in the result section.

Heat Industrial heat load profiles differ from electricity demand patterns. In industry, heat is primarily used for two purposes: *space* and *process heating.* The former considers heating of working environment, the latter is generally related with higher temperature heat generated using fuels that serve as primary source for the industrial processes (e.g. melting of metals). Due to the nature of the end-purposes, it is expected that the heat profiles follow different patterns. Space heating should show a clear seasonal pattern linked with the outdoor temperature. On the other hand, the consumption pattern for process heat is expected to vary according to the type and operation of end-use processes considered as well as on the work-pattern.

As natural gas was found to be the most-used fuel for heat-related processes in industry, we assume that the consumption profile of natural gas represents the patterns of process heat demand in industry. The same is considered for space heating, since district heating and natural gas are also comparable in order of magnitude.

Hourly gas delivery data, for the year 2016, for approximately one third of Danish customers are used (Dansk Gas Distribution, 2016). The gas consumption data, available at end-use level for each company, are separated between space and process heating purposes. The hourly data of gas consumption can be related to the industry sectors by the DB07 Danish branch code. The samples are aggregated to create two load profiles (space and process heat) for each of the 57 sectors, within each of the main categories. Since the number of measurements varies for each company and the number of companies varies for every sector, both the space and process heat profiles represent an average among the company's end-uses and among the companies in the same sectors.

Although this arrangement implies a lower data resolution, it gives a fair representation of the average fuel consumption pattern for the sectors considered. For the exceptional cases in which profiles were missing, a method similar to the one used for the electricity was adopted. As the use of natural gas is not that common in agriculture, no profiles were generated for the industry sectors in the agriculture group.

Results

Electricity The resulting electricity consumption profiles are presented in absolute (MWh) and relative values (%). The relative profiles represent the share of fuel usage in one hour in relation to the yearly consumption. The resulting profiles for each of the 57 sectors are, for verification reasons, grouped according to the five groups. For each group an average profile is generated.

Figures 10.15-10.16 shows that the absolute profiles of the singular sectors within each aggregated group vary in size because of the different amount of energy consumption. Concerning the pattern, they generally follow same weekly profile but differ in the spread between highest and lowest demand.

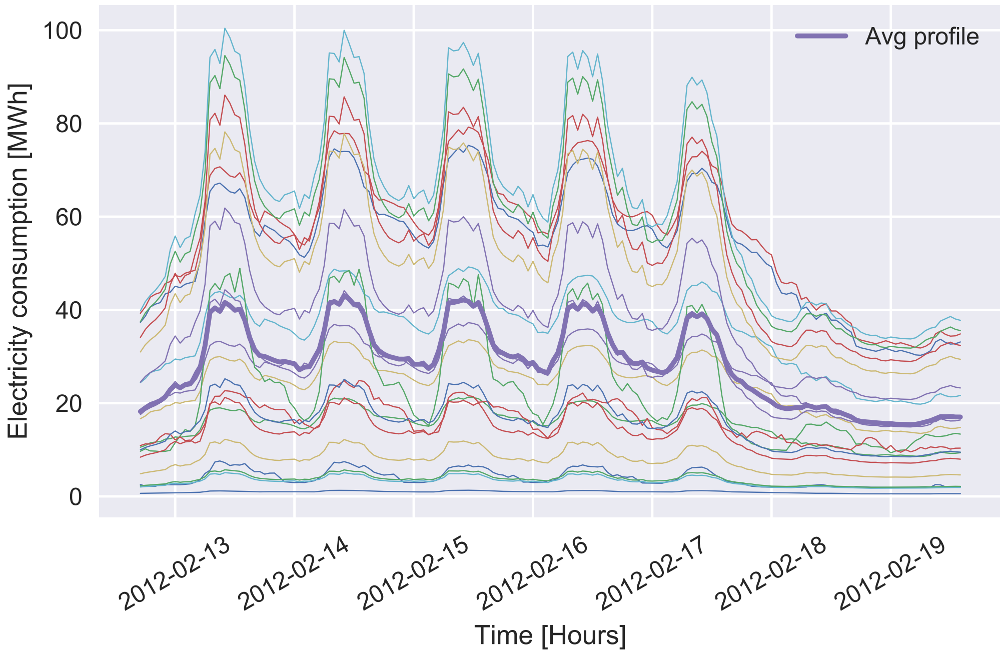


Figure 10.15: Average profile and single profiles of absolute electricity consumption, Production double shift

Figure 10.15 provides an example for the production double shift group.

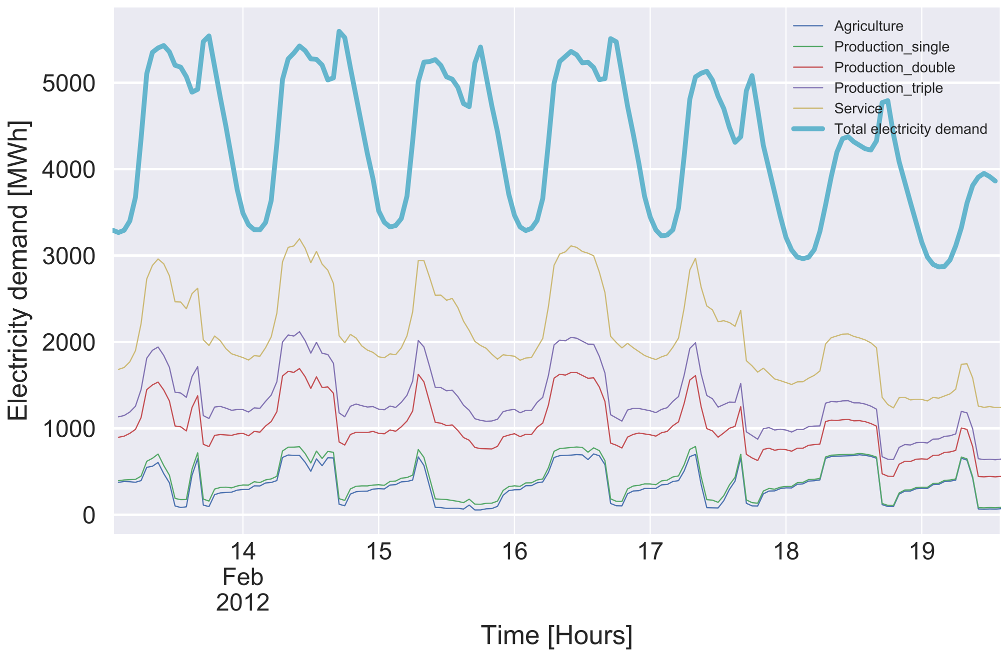
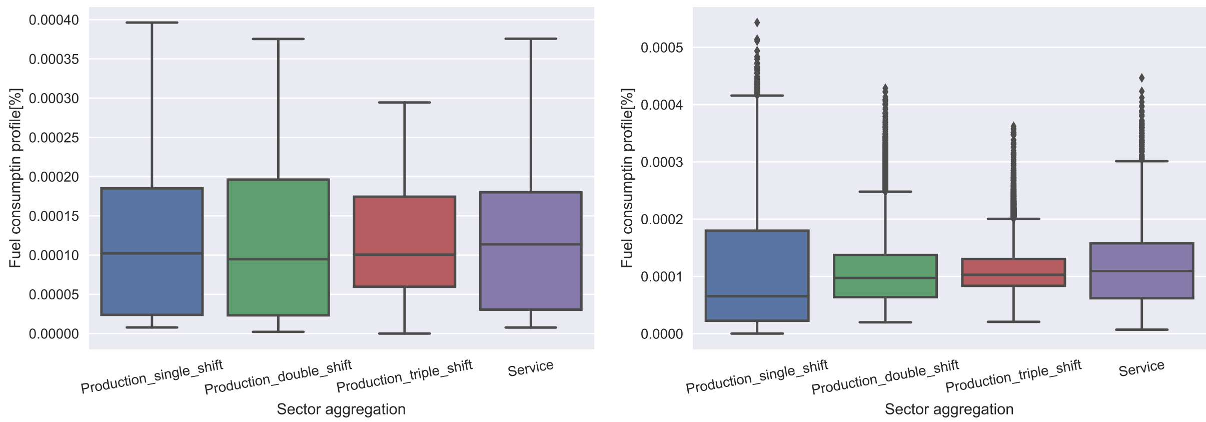


Figure 10.16: Cumulated summed profiles compared to the total electricity demand in a sample week (week 07, 2012).

Compared to the average (blue thick line) the magnitude of electricity consumption varies among the different sectors but still follows the trend of the average. Some exceptions still occur (e.g. small peaks out of weekdays working hours and slightly higher consumption during the weekend) but they are in line with the characteristics of the production double shift group.

Figure 10.16 shows the contribution of the industry to the total electricity demand in Denmark. For the selected sample week, the industrial electricity consumption represents around half (50%) of the total electricity consumption.

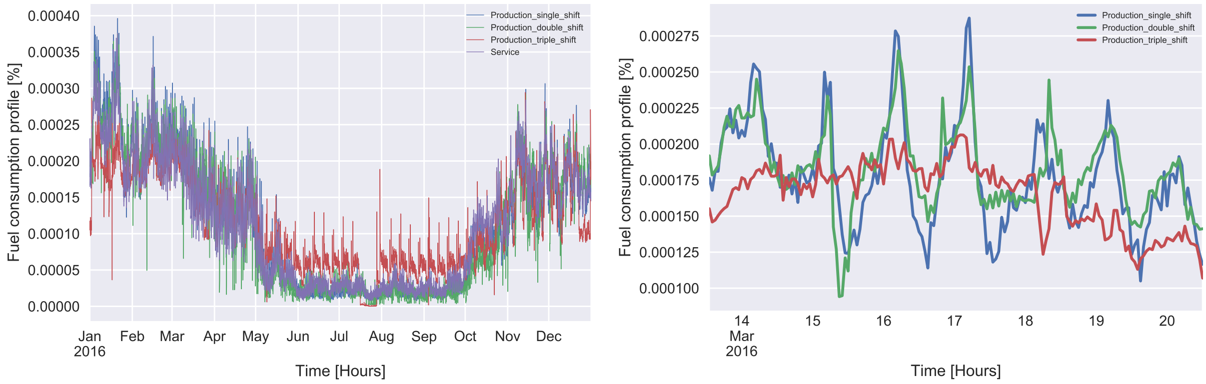
Heat This section presents the findings for the fuel consumption profiles for space and process heating purposes. The newly created relative profiles are analysed by boxplots, presented in Figure 10.17. Similar to the electricity profiles, the reader can observe that the size of the boxplots, and thus the variation of the profile, decreases with the increasing number of shifts. This indicates that triple shift consumption profiles are relatively more stable throughout the year. The boxplots for space and process heating also show, as expected, that most outliers are to be found in process heating rather than space heating.



(a) Space heating *(b) Process heating*

Figure 10.17: Boxplots of relative fuel consumption profiles

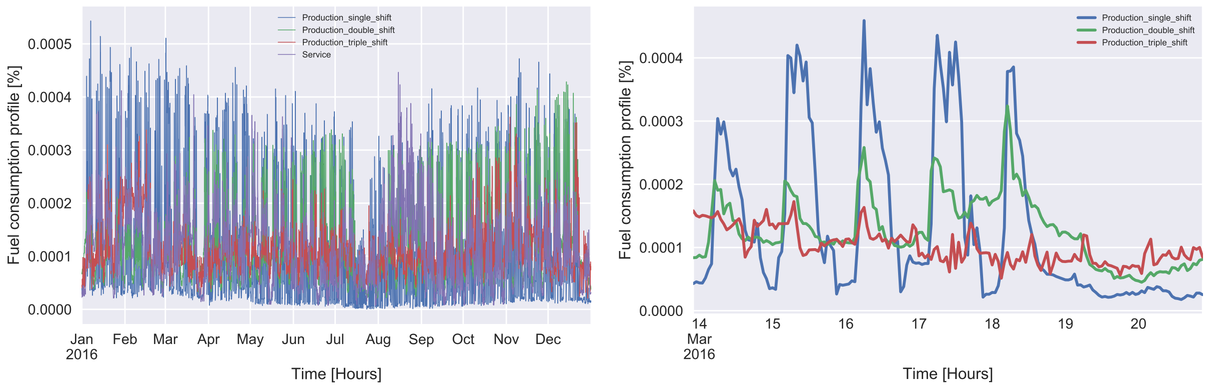
Figure 10.18 and Figure 10.19 present the seasonal variation in fuel consumption for space and process heating on a yearly and weekly scale in relative values. On a yearly scale, the fuel consumption for *space heating* (Figure 10.18a) shows a temperature-related trend, with higher consumption in fall and winter, and a lower consumption during summer and spring. On the contrary, consumption for *processes heating* (Figure 10.19a) shows a more stable profile, not related with the season. In the same figure, the sudden decrease in energy consumption during March-April, July-August and December is related with the closure of activities during holidays (Easter, summer and Christmas respectively).



(a) *Yearly scale* (b) *Sample week*

Figure 10.18: Space heating, seasonal variation of heat consumption profiles

On a weekly scale, the development of the profiles shows diverse trends. For *space heating* (Figure 10.18b), the weekly profile is rather stable within the days, with variations related only with day/night activities (i.e. every day the consumption grows in the morning, reaches two peak within the day and then decreases by night). On the other hand, the fuel consumption profile for *process heat* (Figure 10.19b) present day-related particularities: the energy consumption is higher during the weekdays and lower during the weekends. This is different for the triple-shift profiles which have a rather constant profile throughout the entire week for both for space and process heat.



(a) *Yearly scale* (b) *Sample week*

Figure 10.19: Process heating, seasonal variation of heat consumption profiles

The reader can also notice the different timing of fuel consumption during the week (Figure 10.18b and Figure 10.19b). Production single shift activities operate mainly during day hours and close by night and weekends while production double shift present a slightly flatter profile, implying longer working hours.

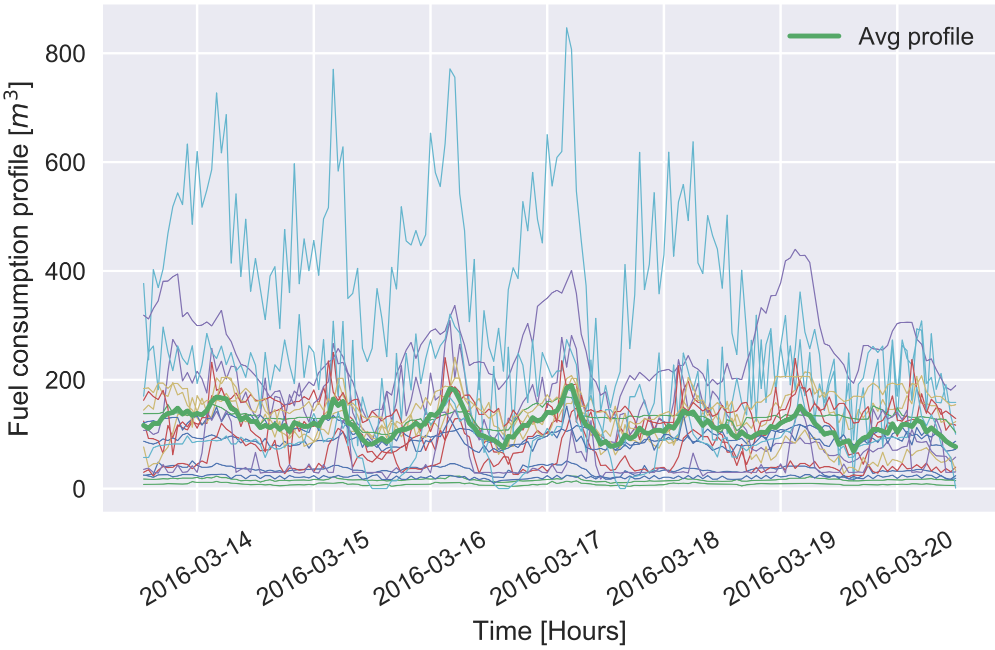


Figure 10.20: Weekly variation of absolute heat consumption profiles, sample week for production single shift sector, Space heating

Figures 10.20-10.21 shows the average profile vs. the singular profiles for processes in production single shift in absolute values of fuel consumption (m^3 natural gas), for a sample week.

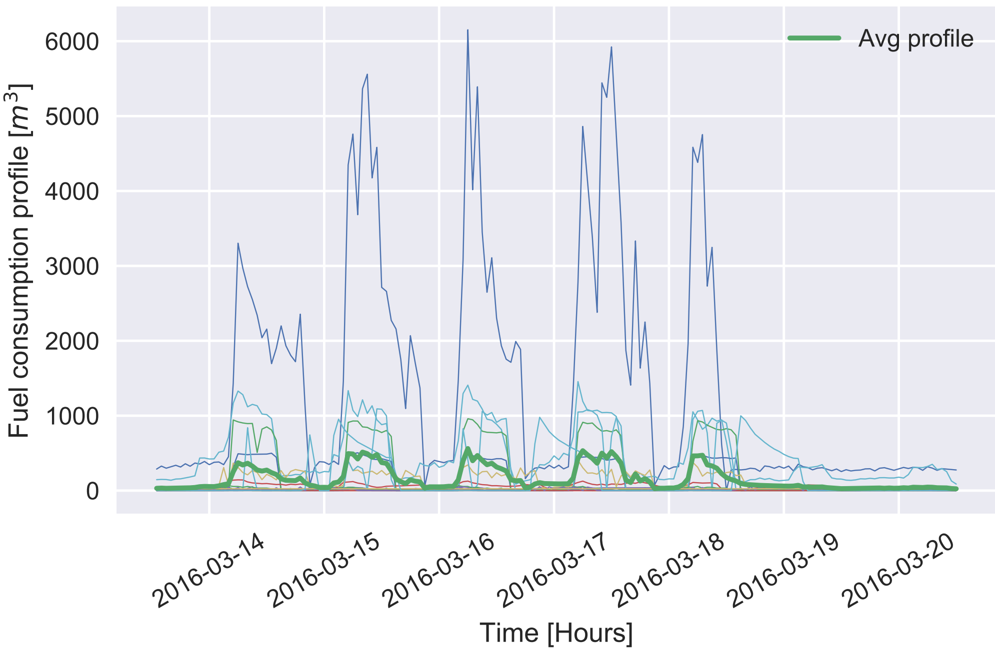


Figure 10.21: Weekly variation of absolute heat consumption profiles, sample week for production single shift sector, Process heating

Focusing on the hourly development during the selected week, the single profiles (thin lines) differ among each other in order of magnitude and pattern. The average profile (thick green line) provides an easier understanding of the general hourly consumption's trend. Summarising, hourly consumption profiles for electricity, space and process heat have been set up and analysed facilitating integrated modelling.

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